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Review

BIM and IFC Data Readiness for AI Integration in the Construction Industry: A Review Approach

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Abstract: Building Information Modelling (BIM) has been increasingly integrated with Artificial Intelligence (AI) solutions to automate building construction processes. However, the methods for effectively transforming data from BIM formats, such as Industry Foundation Classes (IFC), into formats suitable for AI applications still need to be explored. This paper conducts a Systematic Literature Review (SLR) following the PRISMA guidelines to analyse current data preparation approaches in BIM applications. The goal is to identify the most suitable methods for AI integration by reviewing current data preparation practices in BIM applications. The review included a total of 93 articles from SCOPUS and WoS. The results include eight common data types, two data management frameworks, and four primary data conversion methods. Further analysis identified three barriers: first, the IFC format's lack of support for time-series data; second, limitations in extracting geometric information from BIM models; and third, the absence of established toolchains to convert IFC files into usable formats. Based on the evidence, the data readiness is at an intermediate level. This research may serve as a guideline for future studies to address the limitations in data preparation within BIM for AI integration.

Keywords: BIM; AI; IFC; data integration and management; data readiness; data conversion; digital construction; data structure and compatibility

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Citation: Du, S.; Hou, L.; Zhang, G.; Tan, Y.; Mao, P. BIM and IFC Data Readiness for AI Integration in the Construction Industry: A Review Approach. *Buildings* **2024**, *14*, 3305. https://doi.org/10.3390/buildings14103305

Academic Editor: Farook Hamzeh

Received: 22 August 2024
Revised: 16 October 2024
Accepted: 17 October 2024
Published: 19 October 2024

1. Introduction

Building Information Modelling (BIM) has been widely adopted in the Architect, Engineering, and Construction (AEC) industry. The concept of BIM is to streamline design, construction, and facility management processes by centralising information and fostering collaboration among all stakeholders [1]. Artificial Intelligence (AI) has continuously evolved to provide excellent value to industry sectors in recent years. For instance, AI has significantly improved efficiency in the hydroelectric power industry. By optimising gate manoeuvres, it has saved $51,000 annually, conserved 4.32 billion litres of water, and reduced flood risks The deployment of AI technology in the manufacturing industry has resulted in notable advancements, as reported by the National Association of Manufacturers (NAM). After adopting AI, 72% of manufacturers noticed reduced costs and enhanced operational efficiency. Additionally, 51% reported improved operational visibility and responsiveness, while 41% achieved better process optimization and control [2]. As expected, integrating AI into the construction industry results in various solutions for innovative construction management. A Study by Pan and Zhang [3] suggests that the publications related to AI in BIM reached 286 in just the first four months of 2021, accounting for approximately 45.8% of the total publications from the previous year. This quantity even surpasses the total annual publications recorded before 2017.

Establishing AI applications involves training an AI algorithm with a dataset that provides the algorithm with various examples and scenarios. The algorithm learns to recognise patterns, make predictions, or perform specific tasks through this training process, thereby evolving into an effective AI model [4]. Generally, good-quality datasets for AI should be voluminous and diverse, ensuring accuracy, reliable, and formatted for efficient processing [5]. Low-quality datasets will jeopardise the AI's performance. For instance, in research by Daneshjou et al. [6], dermatology AI models experienced a 29–40% performance drop when tested on diverse skin tones not represented in the training dataset.

In the BIM environment, Industry Foundation Classes (IFC) is a file format designed to serve as the central data repository for construction projects [7]. Consequently, leveraging IFC files as datasets for AI training becomes a natural progression. However, the processes for effectively transforming data from IFC format into formats suitable for AI applications still need to be explored. These transformations are crucial for achieving the high-quality standards required by AI systems. While numerous studies have integrated AI applications within BIM environments [3], there is still a significant gap in guidance regarding the specific data preparation methods necessary for optimal AI performance.

Current literature needs comprehensive discussions or frameworks specifically addressing preparing BIM data for AI applications. Some reviews addressed data representation and transformation in general digital construction. Tomczak reviewed the digital construction's Information Requirements (IR) [8]. This paper presented a comparative analysis of different approaches to define IR and discussed how these approaches can be used to encode information in BIM. The limitation is that the concept of IR is defined within the BIM standard, making it not directly adaptable to other data formats. Bloch [9] presented a review of semantic enrichment methods in BIM. This review highlighted that information in BIM can sometimes be inaccessible to other platforms due to its non-explicit representation, necessitating semantic enrichment to facilitate smooth data exchange. However, a limitation noted is that the methods discussed in this work are applicable mainly for input to BIM. Noardo et al. [10] reviewed the use of georeferencing tools for converting between 3D city models and BIM models, but their study is limited to that specific context.

This review paper analyses the current data preparation methods used in BIM environments. It addresses a broader industry challenge: the need for a streamlined, systematic approach to transform highly structured and detailed BIM data into a format suitable for AI algorithms' dynamic, pattern-driven requirements. The goals are to provide a comprehensive overview of how BIM data is prepared for various applications, focusing on data compatibility between BIM and AI environments and identifying challenges and opportunities in this integration.

1.1. Introduction to Artificial Intelligence

The concept of AI was proposed in the 1950s. A group of researchers at Dartmouth college started a research project on artificial intelligence and later funded it as a research field [11]. Many well-known AI concepts, such as the Turing test [12] and Neural Networks (NN) [13], were also proposed during that period.

In the 1980s, the AI industry experienced a booming development with the expert system application [14]. Expert systems utilise logical rules from human experts to solve problems [15] and are considered successful AI applications [16]. With the rapid advancement and widespread adoption of computers in the 2000s, big data become a popular topic [17]. Advanced techniques such as machine learning [18] and deep learning [19] were developed to harness the vast data available, enabling powerful AI applications across various fields. For example, the famous AlphaGo program, which defeated the number-one ranked Go player, was trained using a database with 30 million moves [20]. Similarly, widely adopted image recognition algorithms have been developed based on databases like ImageNet which contain over 14 million images [21]. The transformer architecture was proposed in 2017, which led to a new chapter of the Large Language Model (LLM) [22]. The proposed algorithm formed the powerful ChatGPT series applications that demonstrated overwhelming capability [23,24]. Notably, the latest large language models (LLMs) have begun to utilise multi-modal methods, enabling the processing and understanding of data across different formats. Experts consider this capability a significant advancement toward Artificial General Intelligence (AGI), though it is still in its early stages [25].

The International Organization for Standardization (ISO) produced a specific standard regarding AI as ISO/IEC 22989.2022, "Information technology—Artificial intelligence—Artificial intelligence concepts and terminology" [26], which has been adopted identically in Australia as AS ISO/IEC 22989.2023 [27]. In this document, the modern definition of AI is that the interdisciplinary study and development of AI systems aim to build computer systems that can perform tasks that require intelligence. Users intend AI-enabled machines to perceive specific environments and take actions that fulfil their demands. Over the years, AI has developed into several distinct categories, each with unique characteristics. The fundamental relation of AI categories is demonstrated in Figure 1. The categories reflect the development of AI.

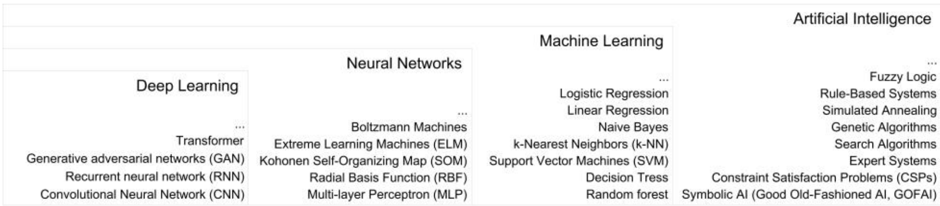

Figure 1. Categories of AI.

The broad concept of AI is defined in the AS ISO/IEC 22989:2023 standard, encompassing much of the work developed before the 2000s. Machine Learning (ML), a subset of AI, shifts away from fixed rule-based systems by enabling machines to learn patterns and rules from large datasets rather than being explicitly programmed. This approach allows machines to improve performance over time by adapting to new data without human intervention [18,28]. NNs are a machine learning model designed based on the structure of neurons in the human brain. They consist of multiple layers of interconnected nodes that work together to process information and learn patterns from data. They excel at identifying complex patterns and making predictions [29]. Deep Learning (DL) is a further advancement of neural networks, characterised using multiple layers of neurons. These deep layers enable the model to learn and extract higher-level, abstract, and semantic information from data. As a result, deep learning models are particularly effective at handling complex tasks, such as identifying images and processing human language [19].

AI processes large datasets to recognise patterns and make predictions. The process begins with collecting and cleaning data and selecting an appropriate model based on the task. During training, the model's parameters are adjusted using algorithms like gradient descent, and its performance is validated with separate test data. Optimisation of hyperparameters ensures the model does not overfit, and once tested, it is deployed for real-world applications. The success of AI is heavily influenced by the quality of data and the model's capacity to adapt to new scenarios [19].

1.2. Applications of AI in the Construction Industry

The construction industry is one of the oldest sectors in human history, with origins dating back to prehistoric times [30]. Today, the sector is vital for the economy of nearly every country worldwide, contributing significantly to infrastructure development and economic growth [31]. Digitalisation in the sector is widely recognised as a major challenge. Efforts to adopt new technologies and processes are slow and face significant complexity [32,33]. In response to these challenges, AI has emerged as a key player in addressing inefficiencies, improving safety, and driving innovation within the industry [34]. A handful of AI applications in the field already demonstrate its potential to transform the construction industry.

Predictive maintenance is a technique that leverages data to detect potential failures before they occur, thereby reducing the frequency of maintenance and enhancing overall reliability. For example, in the research by Cheng et al. [35], the author installed Internet of Things (IoT) devices to collect data and further predict the future condition of MEP components with machine learning algorithms. Construction site safety is another critical area of research, where AI can analyse data from onsite cameras and sensors to identify safety hazards [36], monitor worker compliance with safety protocols [37], and reduce accidents through real-time alerts [38]. AI also plays a vital role in quality control and defect detection. Wang et al. [39] apply Light Detection and Ranging (LiDAR) technology to enable real-time onsite quality control. Yin et al. [40] applied a deep learning algorithm to automate the defect detection of sewer pipes. Project planning and scheduling is a topic that researchers have tried to automate in the previous three decades [41]. Obianyo et al. [42] utilised neuro-fuzzy models and neural networks to evaluate construction schedules and control project activities for optimal performance and efficiency. Cost is a crucial factor in the achievement of a construction project. Ashtari et al. [43] applied a Bayesian network classifier, a type of machine learning model, to assess and predict construction project cost overrun. Mahmoodzadeh et al. [44] applied four machine learning techniques to predict construction cost and duration in a tunnelling project context. Robots and drones are valuable tools in construction. They are a good solution to help prevent injuries and fatalities, which are very common in the construction industry. [45]. You et al. [46] integrated ChatGPT with robots, leveraging the advanced reasoning capabilities of LLMs to automate sequence planning for robot-based assembly in construction tasks. Choi et al. [47] integrated Point Cloud Models (PCMs) with Generative Adversarial Network (GAN) models and fine-tuned algorithms to improve object recognition accuracy in the digital construction site management process. Moreover, AI is also beneficial in terms of green building. For example, Chai et al. [48] proposed a method with improved Particle Swarm Optimization (PSO) and Deep Neural Network (DNN) to improve the accuracy of carbon emissions prediction.

2. Review Methodology

2.1. Research Methodology

This research employs the Systematic Literature Review (SLR) method following the PRISMA guidelines [49] to examine specific topics of interest. SLR is an effective tool for pinpointing gaps in existing research and highlighting areas that require further exploration [50]. The systematic review process, guided by the PRISMA methodology, incluide eight stages. The first stage is preparation, where the research question and protocol are defined. The second stage, identification, involves a comprehensive search of relevant databases. During the third stage, screening, duplicates are removed, and titles and abstracts are initially reviewed. The fourth stage, eligibility, includes assessing full-text articles against predefined inclusion criteria. The fifth stage, data extraction, involves systematically collecting relevant data from the selected studies. The findings are analysed and summarised in the sixth stage, data synthesis. The seventh stage, reporting, presents the results according to PRISMA standards. Finally, the eighth stage, discussion and conclusion, focuses on interpreting the findings, discussing the limitations, and proposing directions for future research.

Figure 2 is the PRISMA flowchart for this research. It illustrates the selection of studies from the initial literature search. Sections 2.3 and 2.4 provide detailed explanations of this selection process.

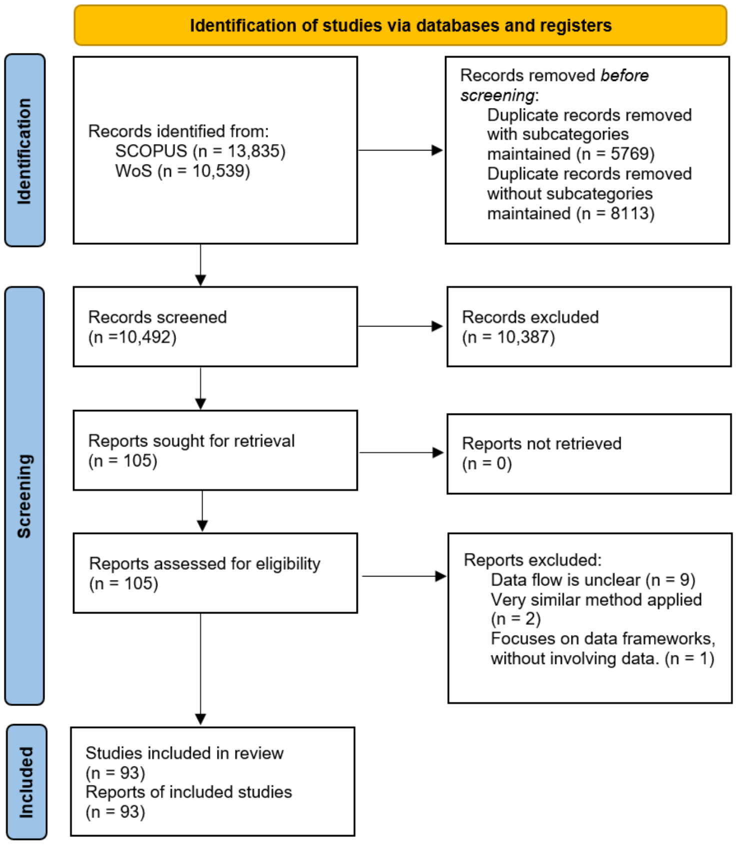

Figure 2. PRISMA flowchart.

2.2. Preparation

This review paper explores how data is managed and processed within AI and BIM environments. This research took the following steps to ensure a systematic and transparent review process:

2.2.1. Development of Protocol

Following PRISMA guidelines, a detailed protocol was developed to maintain consistency and reduce bias during the review process. This protocol specifies the objectives, eligibility criteria, search strategy, and methods for data extraction of this work.

2.2.2. Objectives

The following objectives are proposed based on the research background:

O1—Identify the current methods and approaches for data preparation in AI and BIM environments.

O2—Determine the advantages and disadvantages of each method with respect to efficiency, scalability, and practical application.

O3—Identify the challenges, gaps, and limitations in data readiness and quality for successful AI implementation within BIM environments.

O4—Propose directions for future research aimed at improving data handling and integration between AI and BIM systems.

2.2.3. Research Questions

These objectives further formed the following research questions:

Q1—How is data currently being utilised in BIM applications?

Q2—What are the barriers to data readiness for AI implementation in BIM?

Q3—What are the strengths and weaknesses of the current data preparation methods in BIM?

Q4—How should we prepare data for the future integration of BIM and AI technologies?

2.2.4. Eligibility Criteria

Specific inclusion and exclusion criteria guided the selection of studies. These criteria examine how data is handled across various applications within BIM environments, particularly when integrated with AI technologies. Emphasis is placed on understanding BIM's data management and transformation process as they are applied in different contexts and use cases. This comprehensive approach considers various applications to assess how data is utilised and managed in BIM-enabled workflows.

2.2.5. Information Sources

This research systematically searched relevant studies using SCOPUS and Web of Science (WoS) databases. SCOPUS and WoS are comprehensive, multidisciplinary research databases that provide access to academic journals, conference proceedings, and citation metrics [51]. Given the broad scope of this research, which aims to explore BIM applications across various fields, using such multidisciplinary databases is essential.

2.2.6. Screening and Study Selection

All studies found through the search were screened by their title and abstract, then underwent a full-text review to assess their relevance to the research questions and objectives.

2.2.7. Data Extraction and Management

We used a standardised data extraction form, which can be seen in Appendix A, to collect essential information from the selected studies, including data types, data storage methods, and data preparation techniques.

2.3. Identification

For this research, electronic searches were conducted, with the initial search performed in December 2023. The results from this first round have since undergone a selection process over the following months. An additional search was conducted on 2 September 2024, incorporating new studies published during this period.

This review explores the applications of BIM in combination with various other technologies, broadening the scope beyond its traditional roles in architecture, construction, and building management. The focus is on BIM's entire life cycle, including applications in design, planning, construction, operation, maintenance, and eventual decommissioning. By examining BIM's role throughout these phases, this review highlights its impact across the project life cycle. We searched the following multidisciplinary databases:

- SCOPUS
- Web of Science (WoS)

The essential search criteria are limited to publications in peer-reviewed journals or conferences, focusing on research areas such as engineering, computer science, and related fields, with all works published in English. No specific time range is set for the search to broaden the scope and capture a broader range of results. The primary search query begins with 'BIM' and its synonyms, followed by application-related keywords. Table 1 demonstrates the details of application-related keywords. In this table, the construction process is categorised into four main categories: planning, designing, constructing, and operating and 24 sub-categories based on the work of Meng et al. [52]. Search keywords are also developed accordingly for each sub-category.

Table 1. BIM applications by building lifecycle.

Category	No.	Sub-Category	Search Key Words
Planning	1	Site analysis	("site") AND ("analysis")
	2	urban planning	("urban") AND ("planning")
Designing	3	Visualisation design	("design") AND ("visualisation" OR "visualization")
	4	Collaborative design	("collaborative") AND ("design")
	5	Engineering quantity statistics	("quantity")
	6	Building data collection	("data") AND ("collection")
	7	Energy analysis	("energy") AND ("analysis")
	8	Safety design	("safety") AND ("design")
	9	Sustainable design	("sustainable") AND ("design")
Constructing	10	Construction progress simulation	("construction") AND ("progress") AND ("simulation")
	11	Construction Organisation simulation	("construction") AND ("organisation") AND ("simulation")
	12	Digital construction	("digital") AND ("construction") AND ("application")
	13	Material tracking	("material") AND ("tracking")
	14	Site coordination	("site") AND ("coordination")
	15	Construction visualisation	("construction") AND ("visualisation" OR "visualization")
	16	Construction safety	("construction") AND ("safety")
	17	Green construction	("green") AND ("construction")
operating	18	Completed model delivery	("model") AND ("delivery")
	19	Maintenance plan	("maintenance") AND ("plan")
	20	Facility management	("facility") AND ("management")
	21	Space management	("space") AND ("management")
	22	Disaster management	("disaster") AND ("management")

The proposed search method for the review may face certain limitations, such as publication bias and language bias. Publication bias occurs as studies reporting positive outcomes of BIM applications are more likely to be published, whereas those with neutral or negative results could be underrepresented. Additionally, language bias could arise if the review only includes studies published in English, potentially overlooking significant findings documented in other languages.

In summary, the initial search needs to meet the following criteria:

- Published in peer-reviewed journals or conferences.
- In the research areas of engineering, computer science and related topics.
    - The SCOPUS database's subject areas are limited to computer science, engineering energy, environmental science, and materials.
    - For the WoS database, the categories are limited to engineering civil, construction building technology, computer science interdisciplinary applications, architecture, engineering multidisciplinary, green sustainable science technology, material science multidisciplinary, engineering environmental, computer science artificial intelligence, computer science information systems, transportation science technology, remote sensing, geoscience multidisciplinary, and urban studies.
- Published in English.
- No specific time range is applied, covering publications until 2 September 2024.
- With search string: ("BIM" OR "building information modelling" OR "building information modeling") AND (One of the application sub-categories or its synonyms from Table 1).

2.4. Screening

Table 2 summarises the search results from the two databases; the first column represents the index of sub-categories from Table 1, while the second and third columns list the initial results from SCOPUS and WoS, respectively. After removing duplicate entries, the last column shows the merged results from the two databases.

Table 2. Initial search results.

Sub-Category No.	SCOPUS	WoS	Merged
1	591	391	739
2	313	477	644
3	1313	752	1633
4	814	536	1014
5	616	317	702
6	584	505	769
7	1115	937	1522
8	1102	700	1439
9	1470	1198	2088
10	91	70	124
11	52	4	54
12	731	423	931
13	40	39	62
14	112	77	141
15	982	949	1443
16	1001	1058	1523
17	457	460	697
18	604	315	689
19	135	99	177
20	1187	803	1458
21	420	339	601
22	105	90	155

A total of 18,605 studies resulted from the initial search by category. However, this differs from the number included, as studies will likely appear in multiple related categories. The number of unique studies included is 10,492. The results then go through a title and abstract screening process to determine which will proceed to the full-text review. The inclusion criteria focus on the following points:

- The research must involve the use of BIM environments.
- The research must be an application-based study.
- The research should address data requirements from internal or external sources.
- The research should encompass data preparation, extraction, or storage.
- The research should ideally follow the pattern where data from BIM or external sources is integrated with BIM data for downstream BIM applications.
- The quality of the publication source and the author's area of expertise are also considered.

In the following scenario, the research will also be excluded even if it meets the criteria above:

- Review articles on BIM applications without the introduction of the new method.
- Research that applied the same method for data.

After the screening, 10,387 studies were excluded from the initial results, leaving 105 for full-text assessment.

2.5. Eligibility

A full-text screening is carried out with the following detailed criteria to double confirm their eligibility for this review and extract data from the study:

- Use of BIM Environments: Only studies that explicitly involve using BIM environments were considered. The scope includes research demonstrating the application, modification, or analysis of BIM tools and methodologies within the study.
- Application-Based Research: Studies selected must primarily focus on practical applications of BIM rather than theoretical explorations or social impacts. This criterion ensures that the research is centred on tangible implementations where AI applications will likely land.
- Data Preparation and Utilisation: The research should involve processes related to the preparation and utilisation of data within BIM frameworks for various applications. The scope includes studies that discuss data modelling, data transfer, data management, data integration, or analysis specific to BIM technologies.

For eligible studies, the required information is manually collected in an Excel spreadsheet. The spreadsheet includes title, author, the three major data factors, and a brief description of the paper content. After the full-text review, a total of 12 studies were excluded from the initial results, leaving 93 studies eligible for the report. Since this research focuses on how articles handle data rather than data selection, traditional data bias does not apply in this context.

2.6. Data Synthesis

This review employs a qualitative approach to synthesise the data. The studies are grouped based on four major factors: the type of data involved, how the data is managed within the BIM environment, how the data is converted for its intended purpose, and the advantages and disadvantages of the adopted method. The grouping of factors corresponds to the research questions to obtain direct study results. Microsoft Excel is used to perform data synthesis. A standard data extraction stable is created within Excel to collect related data from each study. The complete table is provided in Appendix A. For each synthesis group, the rationale is provided as the following:

The type of data involved pertains to the characteristics of the data, providing an overview of what has been or needs to be stored in BIM. As data is crucial for AI applications, clarifying the data within BIM is essential before any downstream application can be implemented. Data types from the studies will be classified based on their data source and use cases, and categories will be determined from the field of application. This factor responded to the research question Q1.

Data management is a crucial factor influencing the status of data before application. In BIM environments, the model file serves as the central data hub for the entire project. Since BIM files have their unique data structure, they may or may not meet the requirements of downstream applications. Additionally, external data, such as IoT data collected from sensors, is often integrated with the BIM model and must also be considered. The data status before the application will determine whether the BIM model is directly suitable as an AI dataset. The critical point in determining the data management method is based on where the data is stored before use. In AI scenarios, the sequence of data usage directly influences the feasibility of using BIM model files as a data source for AI applications. This factor responded to the research questions Q2 and Q3.

Data conversion refers to preparing data to meet an application's specific requirements. The training data format in AI applications is critical, as algorithms often require a data structure that differs from the BIM model file format. Therefore, an effective method for preparing data must be established for AI applications. The data conversion method is the process by which data within a BIM model is transformed to meet the application requirements involved. Identifying the methods will address research questions Q2 and Q3.

Altogether, the results from the three factors will respond to research question Q4.

2.7. Reporting

Based on the data synthesis method employed, the selected studies are categorised according to the three distinct factors previously outlined. The studies are systematically grouped for each factor, ensuring that each piece of work is appropriately classified under one specific category per factor. These categories are aligned with this section as follows:

- BIM Model Data Structure: Corresponds to the factor concerning the data type involved.
- Data Management Framework: Relates to managing data within the BIM environment.
- Data conversion: Pertains converting data for its intended use.

It is worth mentioning that this research aims to explore existing data methods rather than assess the popularity of each method. Some methods may appear more frequently in the results, however, this holds little statistical significance. The selection of articles is based on the type of method rather than its frequency of use. However, since current BIM applications are concentrated in a few specific fields, the methods summarised in this paper may only reflect some forms of data utilisation but highlight the more common or relatively mature approaches.

2.7.1. Research Time and Country Map

The research time of the selected works, as demonstrated in Table 3, spans from 2012 to 2024. The number of selected articles varies across the years, with a few years, such as 2012 and 2015, having only one selected work, while other years, like 2020 and 2022, have a significantly higher number of selected works, at 16 and 22, respectively. The selection shows that, although not inclusive of all works in the field, specific periods, particularly from 2019 to 2022, saw more representation in the selected research. The selection for 2024 includes six works, reflecting the most recent research considered in this review.

Table 3. Research time of selected research.

Year	No. of Research	Year	No. of Research
2012	1	2019	9
2013	2	2020	16
2014	3	2021	11
2015	1	2022	22
2016	3	2023	11
2017	5	2024	6
2018	3		
Total	93		

As presented in Table 4, the selected research represents a diverse set of studies from various countries, totalling 93 works. China has the highest representation, with 18 selected studies, followed by the United States with 12 and Italy with 11. Several countries, such as Korea, Turkey, Canada, the United Kingdom, and Slovenia, contributed 6 and 7 studies each. Countries like Australia, France, and Portugal have three studies each, while several countries, including Austria, Belgium, Brazil, Chile, and Egypt, are represented by a single selected study. The selection focuses on a limited number of works from each country, reflecting the specific focus of this review rather than a comprehensive overview of research output from each region.

Table 4. Research country map.

Country	No. of Research	Country	No. of Research
Austria	1	Jordan	1
Australia	3	Korea	6
Belgium	1	Netherland	1
Brazil	1	North Cyprus	1
Canada	6	New Zealand	1
Chile	1	Portugal	3
China	18	Serbia	1
Egypt	1	Singapore	1
France	3	Slovenia	7
Germany	2	Spain	1
Iran	2	Turkey	6
Israel	1	United Kingdom	6
Italy	11	United States of America	12
Total	93		

2.7.2. BIM Model Data Structure

The IFC format is the most widely adopted open BIM model format, recognised as an international standard. The IFC format utilises a tree-like structure to organise and represent building data hierarchically, allowing for efficient management of complex relationships between various building elements and their attributes. The data contained within the IFC format includes building geometry, material attributes, structural components, mechanical systems, spatial relationships, cost estimates, and project scheduling information. Information in the file is stored in various ways, such as numbers, strings, lists, arrays, Boolean values, and references to other entities. Most design software in the market can open IFC files or save files in IFC format. Fetching data from an IFC can also be achieved from a programming library like IfcOpenShell or a visual programming tool like Revit Dynamo [53].

BIM formats, such as IFC, have adopted an open, customisable structure, allowing them to host a wide range of external data. This feature has been well utilised in many research projects where various types of data have been integrated into the model, greatly enhancing the versatility and adaptability of BIM. However, this flexibility has also introduced a challenge—the unpredictability of data types presented in the BIM model, which becomes a hurdle when integrating with AI. Recognising the variety of data types is essential for smooth AI integration. The data types identified from the selected articles are summarised in Table 5. The table identified eight data types through the included studies based on the data source. These types include spatial, weather, GIS, scheduling, IoT, environmental, cost, and facility management. Several data structures were identified: point cloud, image, text, numerical, time-series, geospatial, categorical, ordinal, date, and binary/Boolean.

Based on the summary of data types presented in Table 3, it is evident that the integration and diversity of data within the BIM environment are extensive. Data sources like spatial, weather, GIS, scheduling, IoT, environmental, cost, and facility management employ a range of structures. These include time-series, numerical, geospatial and categorical, highlighting the multifaceted approach needed to manage and utilise these data effectively. This diversity enhances the accuracy and functionality of BIM applications and underscores the importance of interdisciplinary approaches in optimising building management and operational efficiency.

Table 5. Summary of data types.

Data Source	Data Structure	Reference
Spatial	Point cloud, image, text, numerical	[54–95]
Weather	Time-series, numerical, geospatial	[66,96,97]
GIS	Spatial/geospatial numerical, categorical	[98–101]
Scheduling	Time-series, categorical, ordinal, image, date	[78,90,98,102–110]
IoT	Time-series, numerical, binary/boolean, image	[70,96,98,111–118]
Environmental	Time-series, numerical, geospatial, text, image	[55,75,86,93,97,102,111,119–128]
Cost	Time-series, numerical, categorical, date	[64,89,100,106,109,122,129–131]
Facility management	Time-series, numerical, categorical, geospatial, text, date	[68,108,118,132–145]

2.7.3. Data Management Framework

The review revealed notable differences in how researchers handle and use data when working with BIM models and data. There are two significant modes during this process: internal versus external. A summary of data management frameworks from the review is given in Table 6, and a detailed classification of each work can be found in Appendix A. The table summarises the number of studies that adopted the two data management methods. However, the selection process was not designed to include every study involving a specific framework; therefore, the numbers presented do not carry statistical significance.

Table 6. Data management method summary.

Data Management Category	Total Number
External mode	52
Internal mode	41

An internal mode is straightforward to understand. Data from external sources is inserted into the BIM model in the first step and then utilised altogether or simply exacting data from the BIM model and utilised. This mode is more prevalent in applications that emphasise the BIM model. It provides the advantage of seamlessly integrating downstream BIM applications, significantly broadening its range of use. Some examples are provided in Table 7 to explain the mode better. In the three examples shown in Table 7, the underlying principle remains consistent: data are processed and subsequently stored in the IFC file. Downstream applications then directly utilise this inserted data by interpreting the IFC file.

External mode is where the BIM model is utilised solely as a data source, and the data integration is carried out externally. The review shows two main scenarios where external mode is preferred. In cases where external data is time-series, it may not be directly compatible with BIM standards, such as IFC. As a result, merging the data outside the BIM model is often a more straightforward approach. In cases where the application requires minimal data from the BIM model, extracting only the necessary building data more efficient. This approach conserves computational resources. Some examples are provided in Table 8 to explain the mode better. In the three examples shown in Table 6, IFC acts as the downstream application's data source. Required data is extracted from IFC and processed in the first place, then utilised by a dedicated tool or algorithm.

Table 7. Internal mode examples.

Articles	Methodology	Data Management Steps
Reconstructing BIM from 2D Structural Drawings for Existing Buildings by Zhao, Deng, and Lai [57] year 2021	They developed a method for reconstructing BIM models from 2D structural drawings. This work utilised IFC as the data container for the algorithm's output, ensuring that the results could be directly used to generate 3D models in BIM authoring software.	1. Identified objects with R-CNN., 2. Obtain attributes of objects 3. Create object directly in IFC with attributes. 4. Manage data in IFC internally
Tolerance Management Domain Model for Semantic Enrichment of BIMs by Rausch et al. [58] year 2022	They developed a Domain Model (DM) for tolerance management purposes. They collected domain knowledge from industry experts and ontology to analyse possible dimensional difference occurrence in a model. The domain knowledge was injected into the IFC file as a new class to perform the examination.	1. Collecting tolerance domain knowledge from external sources. 2. Create ontology triplets based on collected knowledge. 3. Create a new class in IFC to store tolerance values. 4. Manage tolerance in IFC internally.
Digital Twin-Enabled Built Environment Sensing and Monitoring through Semantic Enrichment of BIM with SensorML by Wang et al. [113] year 2022	They proposed a workflow by integrating IFC and Sensor Model Language (SensorML) to support and automate built-environment sensing and monitoring. With SensorML and digital-twin techniques, they expanded the IFC format to accommodate the sensor data in the model.	1. Extended IFC to align with SensorML. 2. Acquire data from sensors. 3. Store and manage data in IFC internally.

Table 8. External mode examples.

Articles	Methodology	Data Management Steps
An Automatic Generation Method of Finite Element Model Based on BIM and Ontology by Jia et al. [59] year 2022	They introduced a method to generate Finite Element Model (FEM) for building mechanical analysis automatically. Their work combined the IFC format and ontology system to extract data that aligned with FEM model requirements.	1. Develop ontology based on FEM model requirements 2. Apply ontology to IFC file, get required data. 3. Create FEM model in ANSYS software with collected data. 4. Manage data outside of IFC.
Automatically Processing IFC Clipping Representation for BIM and GIS Integration at the Process Level by Zhu et al. [99] year 2022	They researched to convert the IFC clipping representation of BIM into a Geographic Information System (GIS) interpretable format. This research converts the various solid model forms of IFC format into surface models and Boundary Representation (B-Rep).	1. Developed an algorithm that convert IFC data into shapefile format 2. Apply to IFC data. 3. Utilise ArcGIS script to reconstruct in GIS environment.
Global Path Planning Based on BIM and Physics Engine for UGVs in Indoor Environments by Chen et al. [60] year 2022	They improved indoor pathfinding for unmanned ground vehicles (UGVVs) with IFC and A* algorithm. Their work extracted building element boundaries from IFC and created a multi-layer grid map for pathfinding.	1. Ingrate IFC with UGV property. 2. Generate map with semantic layers from IFC. 3. Apply A* algorithm on the layered map.

In summary, the studies show that there are generally two primary data management modes: internal and external. The internal mode integrates data into the BIM model directly, enhancing application scope and seamlessness. The external mode uses the BIM model as a data source, optimising computational resources and accommodating time-series data. Each mode is selected based on project needs and data compatibility, highlighting their distinct advantages in BIM data management.

2.7.4. Data Conversion

Data format compatibility is acritical topic in BIM standards. Different algorithms often demand unique data formats for AI applications, which vary widely, as in Table 3.

This research focuses on understanding the current practice methods to determine the best method for converting the BIM data format to a specified target format. The current data conversion methods retrieved from the selected studies can be classified into four major categories. Table 9 summarises the number of studies that adopted the 4 data conversion methods. However, the selection process was not designed to include every study involving a specific method; therefore, the numbers presented do not carry statistical significance. A detailed discussion of each method is given in Section 3.

Table 9. Data conversion summary.

Data Conversion Category	Total Number
Adopt existing standards and tools.	18
Algorithm-based conversion.	66
Ontology-based conversion.	4
Graph-based conversion.	5

3. Key Finding: Data Format Compatibility

Evaluating the ease with which data can be converted into the required format is essential and critical in AI applications. This research extends this inquiry to assess how data within IFC files can be adapted to various necessary formats. Our review has identified four primary methods for data format conversion. A detailed analysis of each method is imperative to understand its strengths and limitations fully. The knowledge gained from above will enable us to determine the most effective strategies for data transformation in support of AI integration in the AEC industry.

3.1. Method 1: Adopt Existing Standards and Tools

Over the past 20 years of development, numerous data standards and tools have been introduced to facilitate data exchange, especially within BIM software. These standards or tools were developed for various purposes. They are carefully designed to provide immediate capabilities for data format transformation, aligning seamlessly with popular BIM data formats such as IFC. The selected studies show that Building Energy Modelling (BEM) is a popular sector that is adopting this method since various energy simulation-related standards exist [54,63,93,126]. Related applications usually focus on extracting specific data from BIM files into another format.

Adopting existing standards is a relatively straightforward process. Data conversion is usually predefined, and BIM authoring software provides a tool or function. Users only need to install related tools and make essential configurations.

The method's advantage is that it leverages existing standards, typically well-established and meticulously designed with comprehensive considerations for detail. This thorough characteristic ensures that the outputs are robust in quality and consistently reliable, even in large batches. Additionally, this approach does not require users to possess high-level computer skills; a basic understanding of the existing standards is sufficient to achieve effective results.

On the other hand, existing standards often lack flexibility for modification. When data requirements fall outside the predefined scope, users cannot adjust the tools, consequently restricting the use cases for this method.

3.2. Method 2: Algorithm-Based Conversion

Algorithm-based conversion is the most common approach identified in the selected studies. Since the BIM file is positioned as the central data model of construction projects, there is a natural need to extract or integrate data it. This need gives rise to the method discussed. Although summarised under a single category, the actual approaches vary significantly.

This method utilises custom algorithms to transform extracted BIM data into specific target formats. These algorithms are typically developed using traditional programming languages like C# [142] or visual programming languages like Revit Dynamo [144]. BIM authoring software facilitated data extraction through Application Programming Interfaces (APIs). Users can completely customise the output according to their needs.

Versatility is one of the most significant advantages of a dedicated algorithm. Users of the method can establish a complex data conversion process that suits any data requirements. This adaptability allows it to be applicable across the broadest range of scenarios, making it the most broadly utilised among the four.

The drawback of this method is that developing and maintaining such algorithms requires a high level of computer expertise. While the algorithm's versatility is advantageous for general BIM users, effectively utilising it can pose a significant challenge.

3.3. Method 3: Ontology-Based Conversion

Ontology-based methods are language-based approaches typically used to capture higher-level semantics from building data in BIM. These methods utilise ontology triples to systematically structure and interpret the complex relationships and attributes within the data. Ontology triples typically consist of a subject, predicate, and object. They resemble natural language statements that describe the data in terms that are both human-readable and machine-interpretable. In selected studies, customised ontology methods are adopted to transform BIM data into the required format [58,59,134,139].

Users must create a set of ontology triples defining the required information to establish an ontology-based method. These triples act as the foundational rules. Once established, these rules are applied to the data, functioning as a filter to extract the desired information.

The advantage of an ontology-based method is its reasoning capability. This ability allows for more accurate data selection in a complex data environment, such as compliance checking for a BIM model file.

This method has significant disadvantages. It requires users to possess knowledge of the construction domain, advanced computer skills, and a high level of expertise in ontology. This combination of requirements can make it challenging for users without specialised training to implement and utilise ontology-based methods.

3.4. Method 4: Graph-Based Conversion

The well-known graph concept in AEC and BIM is employed to represent data. In graphs, objects are conceptualised as nodes that are interconnected by edges. These edges systematically delineate the relational dynamics among the nodes. Graphs is familiar to the construction industry, as the IFC file format adopts a graph-like structure. The most significant feature of a graph is that elements are described not only by their attributes but are also defined by their relationships with other elements. This feature emphasises the interconnected nature of building components.

Since IFC file have a graph like structure, the establishment of graph-based method usually related to extracting and representing building data for downstream applications [54,56,69,82,85]. At the application level, the process involves two key steps. First, information is extracted from IFC files and stored using a graph data structure. Second, this information is presented using external tools.

The advantages of the graph-based method stem from its inherent compatibility with IFC structures, which facilitates seamless data access. This feature is convenient in construction scenarios as relationship information is challenging to obtain with other methods.

The main drawback of this method lies in the specialised skills required for effective implementation. The graph-based method's output remains in graph structure, which is not readily interpretable for general use. Users must understand graph theory and related skills to represent and utilise this data effectively.

3.5. Data Conversion Conlusion

The review identified four primary data conversion methods from the selected studies. Adopting existing standards is the most straightforward method for general users, but it needs more flexibility to adapt to changing requirements. Conversely, the algorithm-based method offers the most excellent flexibility and versatility but demands a high level of computer proficiency for effective adoption. Ontology-based and graph-based methods are specialised in specific areas. Ontology-based methods excel in tasks related to language interpretation, while graph-based methods are adept at elucidating relationship information. However, both methods require a high degree of specialised skill, which limits their widespread adoption. The algorithm-based method may be the most adaptable due to its flexibility in handling a wide range of data types and complex conversion requirements.

4. Discussion

The review identified three major barriers to AI implementation in the BIM environment. The initial challenge involves the incompatibility of time-series data with the BIM model structure. Secondly, the representation of geometry data in the BIM model is problematic for AI to interpret. The third obstacle is the need for interfaces to extract building data. The subsequent subsections will elaborate on these challenges and two additional findings.

4.1. Overview: AI Integration in BIM

BIM is a digital representation process that facilitates the entire lifecycle of building projects. It offers a common platform for all stakeholders to collaborate and access the most current information [146]. BIM was introduced in the 1970s when Computer-Aided Design (CAD) drafting began to replace hand-drawn drafting [147]. Around the 2000s, the BIM environment began to take shape. At the implementation level, the adoption of BIM is often linked to using specific data formats that follow BIM standards. This approach facilitates cross-discipline collaboration. Currently, the official BIM standard is referred to as ISO 19650, "Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—Information management using building information modelling" [148], which has been adopted identically in Australia as AS ISO 19650.5 and BD-104 [149]. Following the standards, some BIM file formats have also been developed. For example, IFC is the most widely adopted open BIM file format managed by BuildingSmart [7]. An open format, Green Building XML (gbXML), is widely adopted in building energy and performance analysis [150]. CityGML is an open format for 3D city models, usually adopted by geospatial and urban planning applications [151]. Moreover, the Construction-Operations Building Information Exchange (COBie) serves as a performance-based standard for delivering facility asset information, introduced by the U.S. Army Corps [152]. BIM as the digital data hub for construction projects makes it an ideal foundation for AI applications [54]. As a result, numerous applications have emerged, including AI-driven design optimisation [153], construction process automation [154], predictive maintenance [35], clash detection [155], energy efficiency analysis [156], and cost estimation [157]. Although the above studies have showcased the potential of integrating AI-powered BIM, there is still a need to further explore how to effectively convert BIM data into a format suitable for AI applications.

4.2. Data Accessing Barrier: Lack of Time-Series Data Properties

According to the findings presented in Table 3, BIM data originates from various sources and is represented in diverse data structures. To check if BIM environments work with different data types, we need to examine the support BIM formats provide for these types. Building on this, we conducted a detailed analysis of how selected works address various data types and examined the capabilities of the IFC standard [7] in accommodating these needs. The results are summarised in Table 10. As summarised in the table, the IFC format supports several data types. Numerical, date, and spatial or geospatial data types are supported by IFC as basic data formats. Categorical data is supported by the tree-like structure of IFC format itself, and ordinal data is supported using phrasing attributes in IFC. The table also reveals that time-series data structured needs to integrate better with the IFC format. This finding is identified in a growing trend in research efforts to incorporate such data into model files. The intention of incorporating can be found mainly in IoT-related research [70,96,98,111,113–118], with various methods explored to align the data with the IFC format.

Table 10. Summary of data structure.

Data Structure	IFC Compatibility
Numerical	Supported by IFC as a basic data format.
Time-series	Not supported by default. Time-series data will increase over time, and the IFC format is not well suited to accommodate this type of data. A common practice is utilising external databases.
Date	Supported by IFC as a basic data format.
Spatial/geospatial	Supported by IFC as a basic data format.
Categorical	Supported by IFC. The IFC structure is building a categorical concept that entities are inherited from a higher-level class which naturally grants them categorical information.
Ordinal	Supported by IFC. Ordinal features in IFC can be considered another form of phrasing attributes.

Time-series data, characterised by its accumulation of periodic elements over time, is an important data source for the topics. It provides an ideal foundation for implementing AI. However, the IFC format does not have a dedicated structure to handle time-series data. The IFC format allows the model to contain any extra information as new properties. However, the IFC model does not inherently maintain a history or record of these properties' changes. The lack of time-series data support is a prominent barrier for IFC downstream applications that require historical data. A common workaround is introducing external databases to store such data. Databases in IT are now solid and mature technologies. However, using external databases could be better in terms of AI implementation. An external database is not a standard component of BIM standards; thus, it lacks defined rules. Different types of databases could be used across different projects, and the methods for pairing external data with an IFC model may vary from one project to another. This mismatch can pose significant challenges when collecting large-scale data from IFC models. On the other hand, that homogenous data is an essential requirement for AI implementation. Thus, the lack of the ability to handle time-series data is quite a significant barrier. Research towards enabling such ability will promote AI implementation and benefit other applications. For example, it is critical for visualising IoT data in facility management. In conclusion, the inability of IFC to handle time-series data significantly impedes AI implementation. Time-series data is a common and essential data type in this context, necessitating focused research and development to address this barrier.

4.3. Data Accessing Barrier: Heterogeneous Geometry Information

The review also identified that heterogeneous forms of geometry information in IFC are another prominent barrier to AI implementation. Geometric information is the core set of information in construction documents. The collected studies identified spatial features as the most commonly required data source from BIM files, with 42 out of 93 studies [54–95] focusing on geometry. Although the number of collected studies does not support statistical significance, the proportion still reflects the considerable importance of this data type. In the BIM environment, file formats like IFC are designed to store comprehensive building information. They also enable the accurate rendering of building models, reflecting their geometric information. However, the IFC standard [7] indicates that acquiring geometric information directly from IFC files is not as straightforward as it seems. The main reason is that IFC files store geometric information in heterogeneous forms, which intend to facilitate model rendering rather than direct access. The IFC format handles geometry data in various ways due to the complexity of entity shapes, resulting in explicit and implicit geometry representations within the same file. For example, common geometric representations adopted in IFC include parametric profiles, path extrusions, boundary representations (B-rep), and aggregations of geometry [7]. Multiple-format geometric representations allow 3D render to regenerate complex models accurately. However, they pose a big challenge for AI algorithms. Modern AI algorithms or models are all built based on a perceptron framework, which can be expressed in abstract by the following equation:

$$t = f\left(\sum_{i=1}^{n} w_i x_i + b\right) \tag{1}$$

In Equation (1), 'x' denotes the input data, 't' denotes the output data, 'w' and 'b' are the learnable weights, and 'f' is the activation function. From a linear algebra perspective, 'x' is expected to remain consistent throughout the application. Thus, the IFC file's geometry information does not directly apply to AI implementation. One potential solution lies in the final rendering of IFC, where all entities are generated in the same model space. By transforming all entities into a common geometric framework during rendering, inconsistencies and complexities inherent in the IFC geometry representation could be unified. Overall, the presence of heterogeneous geometry information in IFC files significantly impacts the implementation of AI in BIM. This inconsistency in data representation poses a major obstacle, hindering AI from effectively utilising the core data of IFC and thereby impeding the advancement of AI integration in BIM processes.

4.4. Data Accessing Barrier: Lack of Data Extracting Toolchain

As identified in the review, the lack of a data-extracting toolchain for IFC files is another barrier to AI implantation. Although the studies were selected based on applications in BIM with data operations, a consistent methodology has yet to emerge. For example, some research focuses on material data within BIM files. These studies have developed customized tools using various approaches: the ontology method [58,59], Revit Dynamo [120], and the OpenStudio plugin [126]. These methods can adequately edit file content following the IFC format requirements. However, these tools do not offer further functions for converting, pruning, or reorganising data into AI flavour non-standard format. Users have no choice but to utilise either of the three methods above to interpret the IFC file and then manually create a separate workflow to achieve the desired data format. The lack of tools presents a high technical barrier for participants who want to create a database from IFC files. This barrier also increases the difficulty when conducting large-scale data collection. Further research is needed to complete the toolchain, lower the technical barrier, and ultimately establish a smoother conversion workflow.

4.5. Finding: Success of the IFC Standard

Some studies were deemed ineligible for the research during the review selection process. However, they strongly indicate that the design of the IFC standard has been highly effective and successful in achieving data integration across diverse applications. The evidence is summarised in three major aspects. Firstly, IFC formats have proven to be applicable in large-scale adoption. A report from Finland [158] shows that 60% of Finnish 3D planning applications are submitted in IFC format. The industry is generally optimistic regarding this technology as it significantly improves cost efficiency [159,160]. Secondly, research has shown that IFC contains sufficiently rich data. Many research endeavours demonstrate that extracting the required information from IFC files is feasible, underscoring the robustness of the format's integrity. Although specialised algorithms are sometimes needed to extract this data, the inherent information within the format remains rich and adaptable to numerous research scenarios. The research of Mediavilla, Elguazabal and Lasrte [54] supported this data richness. The authors believe the IFC file contains all the necessary data for BEM purposes but lacks a proper extraction method. Thirdly, the flexibility of the IFC format becomes evident in scenarios where external data needs to be integrated with existing building data. It can seamlessly accommodate new entries. Much research has demonstrated the inherent advantages of the expandable feature of IFC.

In pioneering reviews that adopted IFC as the AI training database, it is evident that a universal data format offers significant advantages. This advantage is especially true when homogeneous data is required across projects from different sources [76]. Although IFC seems successful in many ways, it remains subject to particular challenges. For instance, the research by Eslahi et al. [161] illuminates a noteworthy aspect where the standard encounters conversion difficulties. Their findings underscore that exporting a model from Revit into the IFC format and subsequently re-converting it back into a Revit model can lead to data loss. This discovery serves as a reminder that the IFC format, although valuable and widely employed, is not immune to imperfections. This instance highlights a specific area where the format's interoperability might require further refinement. Acknowledging these limitations is pivotal for both practitioners and researchers. It prompts a deeper understanding of the nuances and intricacies surrounding IFC's usage. This understanding, in turn, paves the way for targeted enhancements to ensure a more seamless and comprehensive data exchange ecosystem.

4.6. Finding: Graph as Future for AI in BIM

The review also revealed that graphs are a promising method for data preparation for AI implementation in the BIM environment. There are five studies related to spatial data that adopted graph methods, with applications in design [82], rule checking [69], energy simulation [54], route planning [85], and MEP modelling [56]. These studies demonstrate that the graph method can extract spatial relationship information, showcasing a compelling advantage. As non-Euclidean data, building data is unique compared to standard AI data formats such as numbers, text, audio, and video, all classified as Euclidean data. Apart from values, there are also relations of items that need to be recorded in building data. Traditional file formats may not be efficient in dealing with such data.

The graph methodology, on the other hand, utilises vertices and edges to record value data and relational data. This structure aligns with how the IFC standard stores building data, allowing smooth data transformation. Furthermore, established graph databases like Neo4j offer robust data management tools that support effective querying and storage. Some researchers have tried to convert IFC to Neo4j and acquired positive results. On the AI side, graph-related algorithms also started to emerge. Due to their unique non-Euclidean nature, Graph Neural Networks (GNNs) are considered more complex. The development of GNNs needs to catch up with Euclidean-based AI algorithms. The most common GNN branches nowadays are Graph Convolution Networks (GCN) and Graph Attention Networks (GAT) [162]. They were based on different methodologies, but all demonstrated robust capabilities in various tasks. Such advancements indicate great potential for graph-based AI algorithms. More advancements in graph-based AI algorithm integration with BIM are expected.

4.7. Overview: Data Data Readiness in BIM for AI Implementation

The review observes the prominent trend of how data has been utilised with BIM in recent years. The related research has established a foundation for data exchange between the BIM models and AI applications. From there, we could delve into an overview of data readiness in BIM for AI implementation and respond to the research questions.

4.7.1. Q1—How Is Data Currently Being Utilised in BIM Applications?

Evidence from the review has shown that the data in the BIM model is considered rich and has been utilised in numerous ways. Especially in downstream applications of BIM, such as facility management, combining live data with building data becomes a powerful tool for managing daily operations. On the other hand, the role of the BIM model varies among these applications. In some cases, the BIM model functions solely as a database; in others, it hosts downstream applications. The versatility in roles implies that the relation between the BIM model, downstream applications, and BIM authority software is not yet clearly defined.

In summary, acquiring specific data from a BIM file is straightforward; however, there is no globally recognised process for managing the outputs.

4.7.2. Q2—What Are the Barriers to Data Readiness for AI Implementation in BIM?

The review highlights that extracting data from BIM for use in AI applications remains a significant challenge. It identifies three primary obstacles:

- The absence of time-series data properties.
- The presence of heterogeneous geometry information.
- A comprehensive data extraction toolchain is needed.

Among these barriers, the absence of time-series data properties is particularly critical, as AI applications often rely on identifying patterns within such data to function effectively. Regarding data format compatibility, solutions at the IFC/BIM format level are required. However, significant changes to these standards are unlikely to be implemented shortly. The presence of heterogeneous geometry information in BIM files impedes their direct use as databases for AI applications. While the geometry information remains accessible, managing the output format becomes challenging. This challenge is particularly true when considering the development of an extensive database. The lack of a data extraction toolchain is a minor concern. With the ongoing development of AI in BIM environments and the establishment of data guidelines, the creation of such toolchains is anticipated. Similar toolchain developments have been observed in many other fields applying AI.

4.7.3. Q3—What Are the Strengths and Weaknesses of the Current Data Preparation Methods in BIM?

Method 1: Adopt existing standards and tools. Existing standards are typically well-established and include comprehensive considerations for detail. This feature makes them easy to apply and ensures stable outputs. However, they often need more flexibility to adapt to AI applications' varied and constantly evolving requirements.

Method 2: Algorithm-based conversion. The most versatile method among the four is applying a dedicated algorithm. This approach can deliver robust results for nearly any data requirement. However, developing and maintaining such tools require a high level of computer expertise, which increases the threshold for their easy application.

Method 3: Ontology-based conversion. Ontology methods enhance the semantic understanding of data. This capability enables users to extract information from IFC data under logical conditions. This feature proves especially useful in compliance checking. However, establishing ontologies demands high-level expertise and applies only to specific data scenarios.

Method 4: Graph-based conversion. Graphs are inherently compatible with IFC structures, offering advantages in accessing data. Graph-based methods can facilitate extracting relational information from model files, a common requirement in AEC applications. However, the main drawback of this method lies in the specialised skills required to implement it effectively.

4.7.4. Q4—How Should We Prepare Data for the Future Integration of BIM and AI Technologies?

Based on the review findings, the optimal approach for data preparation in future scenarios would involve establishing a universal standard accompanied by a comprehensive toolchain. Since BIM users often possess limited computing skills, the development of AI integration should prioritise ease of use. Ideally, BIM standards like IFC would natively support time-series data. Such a feature would allow users with a dedicated tool to import or export data from BIM model files. Acquired data could then serve as a training dataset for various AI applications.

4.7.5. Significance, Contribution and Limitation

This research addresses the underexplored area of data preparation in BIM for AI applications, mainly focusing on the IFC format. The research identifies data readiness as intermediate, meaning BIM has been extensively integrated with AI to automate construction processes. However, more methods are needed to transform BIM data into compatible formats, limiting AI's practical application in the AEC industry.

The research's primary contribution is identifying critical advancements in current data preparation and three persistent obstacles in preparing BIM data for AI applications. The research findings established practical guidelines for preparing BIM data for AI integration, highlighting critical areas for future focus. Additionally, this study enhances the adoption of BIM by uncovering new opportunities for integrating AI applications in the construction industry.

However, there are limitations to this study. Firstly, the research concentrates on applications only within BIM environments. Therefore, it may overlook some enlightening data methods from non-Bim AI-related research in the construction industry. Secondly, the selection of studies is constrained by their data requirements, and the quantitative statistics provided in the research lack statistical significance. Therefore, the tendencies observed in each method require further investigation to validate their reliability and applicability. Thirdly, the research primarily focuses on current practices and applications. As a result, it may fail to fully capture emerging trends or the potential for future advancements in AI and BIM integration. This limitation could narrow the scope of the findings and their relevance for rapidly evolving technological landscapes in the construction industry.

4.7.6. Future Directions

Based on the review findings, the research suggests two main future research directions. The first direction concerns a time-series data storage method in the BIM environment. Direct support at the BIM standard level may be the best approach to this issue. However, this support requires careful consideration of all related factors. The process may take a long time to accomplish. Therefore, there is significant potential exists to identify a new method to universally store time-series data in the BIM model. This new method should allow users to easily import and export time-series data and keep a clear connection between the data and the entity in BIM file properties. The second direction regards the tools to extract and input data for AI purposes in BIM files. BIM authoring software is dedicated to the design and construction process. Users require computer skills to get data from BIM files for other purposes. Technical requirements limit the integration of AI and BIM. General BIM users usually need more computer skills, and developers usually need more insight into the industry. A tool is needed to allow general BIM users easy access to the data. With access to building data, professional BIM users could fully utilise the power of AI to improve the construction industry.

4.7.7. Summary of Findings

Based on the evidence from the review findings, the data readiness can be concluded to be at an intermediate level. Significant strides have been made in organising and formatting the data. However, additional enhancements are essential for achieving full compatibility and utility for targeted operations. Critical areas for improvement include enhancing the compatibility for time-series data, standardising the output of geometry data, and developing a dedicated data extraction toolchain. Addressing these aspects will further elevate data readiness for advanced processing and enhance the integration of BIM with AI applications.

5. Conclusions

This paper presents a thorough, systematic review of data readiness in BIM for AI applications, with a particular emphasis on the IFC format. This study evaluates existing methods of preparing BIM data for AI applications, aiming to determine the most suitable strategies to optimise data readiness and usability in AI-driven processes. The research explores how data are prepared in BIM by conducting a systematic literature review following PRISMA guidelines. Ninety-three studies were thoroughly reviewed, identifying eight common data types, two major data management frameworks, and four primary data conversion methods in current BIM applications.

Regarding data types, the review finds that IFC currently does not adequately accommodate time-series data. From the four primary data conversion methods, the review determines that adopting existing standards is the most straightforward method for general users. However, it needs more flexibility to adapt to changing requirements. Conversely, the algorithm-based method offers the most excellent flexibility and versatility but demands a high level of computer proficiency for effective adoption.

Ontology-based and graph-based methods specialise in specific areas: Ontology-based methods excel in tasks related to language interpretation. In contrast, graph-based methods are adept at elucidating relationship information. However, both methods require a high degree of specialised skill, which limits their widespread adoption.

Based on the above evidence, the review concluded that the level of data readiness in BIM and IFC environments for AI integration is intermediate. Further analysis of the reviewed papers yielded several findings. Firstly, in the context of AI applications, the non-homogeneous geometric information within BIM models presents a significant challenge. Secondly, the review has revealed a need for toolchains for IFC data conversion. Thirdly, the IFC format has excelled in building data centralisation as the dedicated BIM data format. Finally, the paper highlights the importance of graph-based data preparation methods in AI implementation for the AEC industry. The research has several limitations. Firstly, it primarily focuses on BIM environments and may miss critical insights from non-BIM AI-related research in construction. Secondly, the study selection is limited by specific data requirements, and the quantitative statistics lack statistical significance. Further investigation is needed to confirm the reliability and applicability of observed trends. Thirdly, focusing on current practices may only partially capture emerging trends or the potential for future advancements in AI and BIM integration. The lack of foresight could limit the applicability of the findings in a rapidly evolving technological landscape.

This research is an excellent foundation for general BIM users aiming to integrate AI into their BIM tasks. Today, construction projects typically use a well-established BIM model. However, no framework exists for the AI-readiness of BIM data. Improper data management practices affect the effectiveness of subsequent AI applications and create unnecessary workloads for management teams. The findings of this research serve as an exemplary reference for AI data preparation. Users could refer to this research to improve model data readiness and streamline the application process.

The research has highlighted the current state of data readiness and its challenges. Future research should enhance precision and effectiveness of the data exchange process, address the challenges associated with data structure interchangeability, and explore the integration of graph-based methods to process building data in the IFC format. Targeting the above aspects will pave the way for an AI-integrated AEC industry that advances construction efficiency. Additionally, it will ensure sustainable development throughout the building lifecycle.

Author Contributions: Conceptualization, S.D. and L.H.; methodology, S.D., L.H. and P.M.; investigation, S.D., L.H. and G.Z.; resources, S.D. and G.Z.; data curation, S.D.; writing—original draft preparation, S.D.; writing—review and editing, S.D., L.H. and Y.T.; visualization, S.D. and P.M.; supervision, L.H., G.Z., Y.T. and P.M.; project administration, G.Z. and Y.T.; funding acquisition, G.Z., Y.T. and L.H. All authors have read and agreed to the published version of the manuscript.

Funding: We extend our heartfelt appreciation to the "ARC Industrial Transformation Research Hub for Transformation of Reclaimed Waste Resources to Engineered Materials and Solutions for a Circular Economy" (Grant No. IH200100010) for their invaluable financial support.

Conflicts of Interest: The authors declare no conflict of interest.

Glossary

Term	Definition
BIM (Building Information Modelling)	A digital representation of an asset's physical and functional traits used for decision-making across its lifecycle, as outlined in ISO 19650.
IFC (Industry Foundation Classes)	A standard data model and file format for sharing architectural and construction data across different software applications, supporting the entire lifecycle of a building project. Developed by BuildingSMART.
AI (Artificial Intelligence)	Defined by ISO/IEC 22989 as the ability of a system to perform tasks that typically require human intelligence, such as reasoning, learning, and self-improvement.
Data Integration and Management	The process of combining data from different sources to provide a unified view, along with the administration of data throughout its lifecycle. This involves ensuring data accuracy, availability, and accessibility.
Data Readiness	The measure of data's preparedness for use in analysis or operations, assessing its quality, completeness, and appropriateness for specific tasks.
Data Conversion	The process of transforming data from one format or structure to another to meet the requirements of different systems or applications.
SLR (Systematic Literature Review)	A methodical evaluation and synthesis of research studies that addresses a clearly formulated question, using systematic and explicit methods to identify, select, and critically appraise relevant research.
PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)	A set of guidelines designed to improve the reporting of systematic reviews and meta-analyses, ensuring clarity and transparency in how review findings are derived from data.
Digital Construction	The use of digital tools and technologies, such as BIM, to enhance the planning, execution, and management of construction projects, improving efficiency, accuracy, and collaboration.
Data Structure and Compatibility	Refers to the organisation and format of data that enable adequate storage, processing, and exchange across different systems or applications, ensuring seamless integration and functionality.
Machine Learning (ML)	A subset of artificial intelligence that enables systems to learn and improve from experience without being explicitly programmed, using algorithms to analyse data, learn patterns, and make decisions.
Deep Learning (DL)	An advanced branch of machine learning that uses layered neural networks to analyse various levels of data features, enabling the modelling of complex patterns and decision-making processes.
Application Programming Interfaces (APIs)	Sets of protocols and tools for building software and applications, allowing different software programs to communicate with each other and enabling the integration of various functionalities.
Generative Adversarial Network (GAN)	A type of machine learning framework where two neural networks contest with each other to generate new, synthetic instances of data that can pass for real data, improving both generation and discrimination capabilities.
Deep Neural Network (DNN)	A type of artificial neural network with multiple layers between the input and output layers, which learns to model complex relationships in data through a deep architecture, enhancing performance on tasks such as classification and regression.
Graph Neural Networks (GNN)	A type of neural network designed to directly operate on graph structure data, capturing dependencies within graph data efficiently.
Graph Convolution Networks (GCN)	A subtype of GNN that applies convolutional neural network concepts to graphs, effectively aggregating information from neighbors through layers.
Graph Attention Networks (GAT)	Another subtype of GNN that leverages attention mechanisms to weigh the influence of nodes in a graph, allowing for more dynamic feature learning from neighbors.

Abbreviations

BIM	Building Information Modelling
AI	Artificial Intelligence
IFC	Industry Foundation Classes
SLR	Systematic Literature Review
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
WoS	Web of Science
AEC	Architect, Engineering, and Construction
NAM	National Association of Manufacturers
LLM	Large Language Model
AGI	Artificial General Intelligence
ISO	The International Organization for Standardization
ML	Machine Learning
DL	Deep Learning
IoT	Internet of Things
LiDAR	Light Detection and Ranging
PCMs	Point Cloud Models
GAN	Generative Adversarial Network
PSO	Particle Swarm Optimization
DNN	Deep Neural Network
FEM	Finite Element Model
GIS	Geographic Information System
UGVV	Unmanned Ground Vehicles
BEM	Building Energy Modelling
API	Application Programming Interfaces
CAD	Computer-Aided Design
gbXML	Green Building XML
COBie	Construction-Operations Building Information Exchange
GNN	Graph Neural Networks
GCN	Graph Convolution Networks
GAT	Graph Attention Networks

Appendix A Selected Articles

Article 1	Title: Reconstructing BIM from 2D Structural Drawings for Existing Buildings		
Year: 2021	Data types:	Data management:	Data conversion:
Zhao, Deng, and Lai [57]	Spatial	External	Algorithm based
Description: This work explores a hybrid approach to converting traditional 2D architectural drawings into 3D BIM model. This approach utilises advanced techniques in computer vision, neural networks, and OCR (optical character recognition) to extract information from drawings of structural elements, including grids, beams, and columns. The study highlights that the automated generation of BIM improves the accuracy and efficiency of managing existing buildings, though challenges such as drawing inconsistencies and missing height data remain to be fully addressed.			

Article 2	Title: Tolerance management domain model for semantic enrichment of BIMs		
Year: 2022	Data types:	Data management:	Data conversion:
Rausch et al. [58]	Spatial	Internal	Ontology based
Description: This work presents a framework for managing dimensional variability in construction through BIM. The authors propose the ToleranceDM, a domain model that consolidates existing knowledge on tolerance management into a standardised system, using two case studies in the construction domain. This model allows for the automated computation of tolerance compliance, enhancing communication of tolerance requirements in the field, and aims to reduce defects and rework by improving process benchmarking and compliance validation.			

Article 3	Title: Digital Twin-Enabled Built Environment Sensing and Monitoring through Semantic Enrichment of BIM with SensorML		
Year: 2022	Data types:	Data management:	Data conversion:
Wang et al. [113]	IoT	Internal	Algorithm based
Description: This research explores how digital twins (DT) are integrated with BIM for enhanced monitoring of environmental conditions in buildings. By using SensorML, the approach semantically enriches BIM, enabling real-time data acquisition from sensors to monitor structural and environmental factors. This integration provides a more dynamic, data-driven understanding of the built environment, supporting predictive maintenance and performance optimisation.			

Article 4	Title: IFC+: Towards the Integration of IoT into Early Stages of Building Design.		
Year: 2022	Data types:	Data management:	Data conversion:
Ruiz-Zafra, Benghazi and Noguera [114]	IoT	Internal	Algorithm based
Description: This work introduces a framework for integrating IoT technologies into BIM at the design phase, rather than post-construction. The proposed IFC+ extension to the IFC standard adds new entities to support IoT scenarios, enabling smart environments like smart buildings to be managed from the outset. This method improves both cost estimation and facility management while also streamlining the integration of IoT with building automation and control systems, leading to a more cohesive and comprehensive lifecycle management of building infrastructure.			

Article 5	Title: Automated and Interconnected Facility Management System: An Open IFC Cloud-Based BIM Solution.		
Year: 2022	Data types:	Data management:	Data conversion:
Matarneh et al. [104]	Facility management	Internal	Existing standard
Description: This study introduces a cloud-based system that integrates the IFC standard with BIM for facility management. This system automates the exchange of asset information, reducing data redundancy and manual input in managing facilities. It also supports the integration of facility management data into BIM, enabling seamless, real-time access and interaction with building information throughout the lifecycle of the facility.			

Article 6	Title: Formalization of Occupant Feedback and Integration with BIM in Office Buildings.		
Year: 2021	Data types:	Data management:	Data conversion:
Ergen et al. [145]	Facility management	Internal	Algorithm based
Description: This work develops a semantic data model in order to capture and integrate occupant feedback with BIM. The model structures previously unorganised feedback and integrates it into facility management systems, enhancing operations and decision-making. The study includes a prototype and a case study that demonstrate how the system allows continuous data collection, contextual integration with geometric information, and improved facility management through visualisation and analysis tools			

Article 7	Title: An Automatic Generation Method of Finite Element Model Based on BIM and Ontology.		
Year: 2022	Data types:	Data management:	Data conversion:
Jia et al. [59]	Spatial	Internal	Ontology based
Description: This study introduces a novel approach that integrates BIM with ontology to automate the generation of Finite Element Models (FEM) for structural analysis. The method leverages the IFC standard, extracting necessary spatial and material information from BIM, and using ontology-based reasoning to determine element types and mesh generation. This process streamlines the traditionally manual conversion of BIM models to FEM, improving efficiency and accuracy in structural analysis. A prototype was developed to validate the method, demonstrating its potential to optimize design workflows in construction.			

Article 8	Title: Automatically Processing IFC Clipping Representation for BIM and GIS Integration at the Process Level.		
Year: 2020	Data types:	Data management:	Data conversion:
Zhu et al. [99]	Spatial	External	Algorithm based
Description: This research addresses the challenge of converting geometric data between BIM and GIS. BIM and GIS use different modelling paradigms, which complicates the integration of their datasets. The study proposes an automated process to convert IFC clipping representations into the GIS-compatible shapefile format. This method enhances efficiency by minimising manual intervention, especially in handling complex geometric representations like unbounded half spaces. The approach was validated using four IFC models, showing that increasing boundary size had little effect on file size but slightly increased processing time.			

Article 9	Title: Global Path Planning Based on BIM and Physics Engine for UGVs in Indoor Environments.		
Year: 2022	Data types:	Data management:	Data conversion:
Chen et al. [60]	Spatial	External	Algorithm based
Description: This work presents a system that combines BIM and a physics engine to optimize path planning for unmanned ground vehicles (UGVs). This method uses BIM to provide accurate spatial information about the environment and a physics engine to simulate vehicle movement. The system automates the generation of optimal routes in complex indoor environments, considering both geometric constraints and physical vehicle dynamics, thus improving UGV navigation efficiency.			

Article 10	Title: A BIM-Based Method to Plan Indoor Paths.		
Year: 2020	Data types:	Data management:	Data conversion:
Hamieh et al. [61]	Spatial	External	Algorithm based
Description: This work introduces a system called BiMov, which uses BIM models to automate indoor path planning within complex buildings, specifically in the IFC format. The method involves separating the topological analysis of the BIM model from its semantic and geometric aspects to generate detailed navigation graphs. These graphs take into account the mobility patterns of individuals or objects as well as the functional accessibility of spaces and transitions, including doors and stairs. The system offers different levels of detail depending on the mobility needs, ranging from simple graphs for architectural design validation to detailed meshes for heavy objects or autonomous vehicles.			

Article 11	Title: A BIM-Based Coordination Support System for Emergency Response.		
Year: 2021	Data types:	Data management:	Data conversion:
Feng et al. [62]	Spatial	External	Algorithm based
Description: This work explores a framework that integrates BIM with indoor location technologies to improve communication and task coordination during emergencies like fires. The system, called BIMIL, automates the extraction, transformation, and visualisation of BIM data into simplified formats containing essential emergency information, such as egress points and fire ratings. This approach enhances decision-making for on-site coordinators, enabling them to navigate and manage resources more efficiently in low-visibility environments.			

Article 12	Title: IFC-Based BIM-to-BEM Model Transformation.		
Year: 2020	Data types:	Data management:	Data conversion:
Ramaji, Messner and Mostavi [63]	Spatial	Internal	Existing standard
Description: This study explores the transformation of BIM data into BEM data to facilitate energy performance simulations. This process leverages the IFC standard for interoperability between BIM and energy modelling software, aiming to reduce errors and improve automation in the conversion process. The researchers developed an extension for OpenStudio, enabling the automatic transformation of BIM files into BEM formats via BIMserver. This method was validated through case studies, comparing actual and predicted energy demands to assess the workflow's accuracy.			

Article 13	Title: 3D Model-Based Quantity Take-Off for Construction Estimates		
Year: 2017	Data types:	Data management:	Data conversion:
Han et al. [64]	Spatial	Internal	Algorithm based
Description: This work focuses on improving cost estimation accuracy and efficiency in the construction industry using BIM. It employs 3D models to automate the extraction of material quantities, reducing reliance on manual, error-prone methods. The paper demonstrates how BIM's integration with quantity take-off processes significantly enhances precision in cost planning and allows dynamic updates when design changes occur, contributing to better resource management and more reliable project bidding.			

Article 14	Title: 3D IoT System for Environmental and Energy Consumption Monitoring System		
Year: 2021	Data types:	Data management:	Data conversion:
Mataloto et al. [111]	Environmental	External	Algorithm based
Description: This work presents a system designed to monitor energy usage and environmental parameters in buildings. It combines IoT sensors with 3D modeling to gather real-time data on humidity, temperature, and energy usage, displaying the information through easy-to-understand 3D models. This system aims to engage users by displaying data in a comprehensible way, encouraging behavioural changes that reduce energy consumption, and supporting more sustainable energy management in building environments.			

Article 15	Title: A BIM and machine learning integration framework for automated property valuation		
Year: 2021	Data types:	Data management:	Data conversion:
Su et al. [163]	Spatial, cost	External	Algorithm based
Description: This work proposes an integration framework that combines BIM and ML for automated property valuation. The framework comprises a comprehensive database analysis, an IFC-based data extraction algorithm, and an enhanced valuation model (GA-GBR) optimised using genetic algorithms. By leveraging BIM data and ML models, the proposed approach aims to improve the accuracy and efficiency of property valuation, enabling professionals to utilize value-relevant design information more effectively throughout various stages of AEC projects.			

Article 16	Title: A BIM based tool for assessing embodied energy for buildings		
Year: 2018	Data types:	Data management:	Data conversion:
Nizam et al. [119]	Environmental	External	Existing standard
Description: This work developed a framework to estimate the embodied energy content directly within the native BIM environment. The process utilises data from existing Life Cycle Assessment (LCA) databases to match embodied energy coefficients with the materials specified in the BIM model. The resulting energy assessments provide supplementary information for evaluating the overall environmental impact of construction projects.			

Article 17	Title: Photogrammetry and deep learning for energy production prediction and building-integrated photovoltaics decarbonization		
Year: 2024	Data types:	Data management:	Data conversion:
Abouelaziz and Jouane [65]	Spatial	External	Algorithm based
Description: This work developed a method that combines photogrammetry and DL to predict energy production and support decarbonisation through building-integrated photovoltaics (BIPV). The study utilised photogrammetric data to create detailed 3D models of buildings, which were then analysed using deep learning algorithms to predict the energy output of BIPV systems. The contributions include a novel integration of photogrammetry and AI techniques for accurate energy production prediction, enhancing the optimization and deployment of BIPV systems for sustainable building practices.			

Article 18	Title: Interoperability between building information models and software for lighting analysis		
Year: 2013	Data types:	Data management:	Data conversion:
Aghemo et al. [66]	Spatial, weather	External	Existing standard
Description: This paper developed a method to enhance interoperability between BIM and software used for lighting analysis. It involved utilizing data from BIM models, specifically geometric and material information, to seamlessly integrate with lighting simulation tools. The contributions include improving the efficiency and accuracy of lighting analyses by minimizing data loss and reducing the need for manual data re-entry, thereby streamlining the design and evaluation process in architectural projects.			

Article 19	Title: Augmented reality system for facility management using image-based indoor localization		
Year: 2019	Data types:	Data management:	Data conversion:
Baek et al. [67]	Spatial	External	Algorithm based
Description: This paper presents the development of an augmented reality (AR) system for facility management, utilising image-based indoor localisation techniques. It involved collecting and utilising image data of indoor environments to accurately determine user positions, integrating this information with facility management databases containing building layouts and maintenance records. The contributions include enhancing the efficiency of facility management tasks by providing real-time, location-specific information through AR, improving maintenance operations, and reducing operational time and costs.			

Article 20	Title: Enhancing the efficiency of structural condition assessment by integrating building information modeling (BIM) into vibration-based damage identification (VBDI)		
Year: 2019	Data types:	Data management:	Data conversion:
Bahmanoo et al. [68]	Spatial, Facility management	External	Algorithm based
Description: This paper developed a method to integrate BIM into Vibration-Based Damage Identification (VBDI) to enhance the efficiency of structural condition assessments. It involved using BIM data, including detailed structural models and material properties, to inform and improve the VBDI process. The contributions include increasing the accuracy and speed of damage detection in structures by leveraging BIM data within VBDI, thus improving maintenance planning and structural safety.			

Article 21	Title: Developing A Rule-Based Dynamic Safety Checking Method for Enhancing Construction Safety		
Year: 2022	Data types:	Data management:	Data conversion:
Bao et al. [69]	Spatial	External	Graph based
Description: This study integrates BIM with rule-based and topology-driven safety checks to enhance dynamic construction site safety. The method extracts object attributes and spatial relationships within the BIM model into a graph-based representation to dynamically assess safety risks throughout the construction process. Its application was tested in real-world scenarios, demonstrating the ability to identify and mitigate pre-construction hazards, thereby improving safety management and reducing risks caused by design flaws or construction changes.			

Article 22	Title: Integration of life cycle data in a BIM object library to support green and digital public procurements		
Year: 2020	Data types:	Data management:	Data conversion:
Barbini et al. [129]	Cost	Internal	Existing standard
Description: This work presents a method to integrate life cycle assessment (LCA) and life cycle costing (LCC) data into BIM libraries. This integration supports public procurement processes by allowing decision-makers to evaluate environmental and economic impacts across the life cycle of construction projects. The approach, tested with urban furniture in Italy, offers a workflow that facilitates comparisons between contractor proposals based on sustainability parameters, aiding in greener and more efficient procurement strategies			

Article 23	Title: Implementation of an interoperable BIM platform integrating ground-based and remote sensing information for network-level infrastructures monitoring		
Year: 2022	Data types:	Data management:	Data conversion:
D'Amico et al. [100]	GIS	External	Algorithm based
Description: This work focuses on creating an interoperable BIM platform that combines data from non-destructive ground-based methods like Mobile Laser Scanners (MLS) and Ground Penetrating Radar (GPR) with satellite-based remote sensing for monitoring infrastructures like bridges and viaducts. This integrated approach aims to improve the efficiency of infrastructure management by providing a unified platform for real-time monitoring and data analysis. The study demonstrates the platform's potential in offering a comprehensive view of infrastructure conditions, aiding asset managers in risk assessment and maintenance planning			

Article 24	Title: A Digital Twin prototype for smart parking management		
Year: 2022	Data types:	Data management:	Data conversion:
Zou et al. [70]	Spatial, IoT	Internal	Algorithm based
Description: The study developed a digital twin system that aimed at improving parking management efficiency. This prototype integrates real-time data from ground sensors, cameras, and IoT devices to create a virtual replica of parking lots, enabling dynamic monitoring and prediction of parking space availability. The system enhances user experience with the apbbility of real-time guidance and helps operators optimise parking space utilization. This approach aims to address urban parking challenges while promoting efficient management			

Article 25	Title: A Case Study of Embedding Real-Time Infrastructure Sensor Data to BIM		
Year: 2014	Data types:	Data management:	Data conversion:
Chen et al. [96]	IoT, weather	Internal	Algorithm based
Description: This work explores the integration of live sensor data with BIM for monitoring infrastructure performance. Specifically, it uses a geothermal bridge deck with embedded sensors to track temperature data in real-time. This ability is essential for evaluating the condition of the deck under different weather conditions. The data collected from the sensors are linked to an IFC-based BIM model, allowing for dynamic updates and visual monitoring within BIM software like Revit. This integration enhances decision-making for facility managers by providing continuous condition assessments of infrastructure			

Article 26	Title: Automatic indoor as-built building information models generation by using low-cost RGB-D sensors		
Year: 2020	Data types:	Data management:	Data conversion:
Li et al. [115]	IoT	Internal	Algorithm based
Description: This work presents a framework for generating as-built BIMs using affordable RGB-D sensors. The proposed system captures indoor environments using depth and RGB images and applies algorithms such as semantic segmentation and 3D reconstruction to process the data into a BIM model. The study demonstrates that the method offers high accuracy (98.6% for dimensional reconstruction) while significantly reducing data collection and processing times compared to traditional methods like Terrestrial Lidar Systems (TLS), making it both efficient and cost-effective.			

Article 27	Title: Supply chain management for modular construction using building information modeling		
Year: 2023	Data types:	Data management:	Data conversion:
Liu et al. [98]	Scheduling, GIS, IoT	Internal	Algorithm based
Description: This study focuses on how BIM, integrated with Internet of Things (IoT) and Geographic Information Systems (GIS), can enhance supply chain logistics in modular construction projects. By using BIM to store detailed information about modules, and GIS to track their transport, the system helps to simulate and predict logistical risks, such as module delivery delays, in real time. The implementation of a digital twin platform, tested in a case study, demonstrated improved efficiency in managing module deliveries and reducing project delays. This approach allows for better coordination between off-site manufacturing and on-site assembly, which is critical for the success of modular construction projects, especially in complex urban environments.			

Article 28	Title: IoT open-source architecture for the maintenance of building facilities		
Year: 2021	Data types:	Data management:	Data conversion:
Villa et al. [133]	Facility management	Internal	Algorithm based
Description: The work presents a framework for integrating IoT and BIM to enhance predictive maintenance in facility management. This system utilises IoT sensors to collect real-time data on building components, which is then visualised through BIM for monitoring and maintenance purposes. The framework aims to improve decision-making and reduce costs by providing accurate, real-time fault detection and performance analysis, particularly applied to HVAC systems. The open-source approach offers flexibility, enabling facility managers to detect issues early and implement timely maintenance interventions			

Article 29	Title: Work package-based information modeling for resource-constrained scheduling of construction projects		
Year: 2020	Data types:	Data management:	Data conversion:
Wang et al. [103]	Scheduling	Internal	Existing standard
Description: This work presents an integrated approach that connects BIM with resource-constrained project scheduling problem(RCPSP) model. The authors developed a model that enables seamless data flow from BIM to RCPSP, addressing gaps in data integration. This method automates schedule generation and improves data transfer efficiency, reducing input and modeling time by up to 85%. The model supports enhanced resource allocation and scheduling in complex construction projects			

Article 30	Title: BIM Analysis Method of Material Consumption for Construction Engineering Based on Pix2pix Algorithm		
Year: 2023	Data types:	Data management:	Data conversion:
Cao et al. [102]	Environmental	External	Algorithm based
Description: The study introduces an innovative approach that combines BIM with the Pix2pix deep learning algorithm to estimate material consumption in construction projects. The method enhances the accuracy of material predictions by utilising image-to-image translation techniques, allowing the system to generate more precise models of material requirements based on input data from BIM. This approach enhances efficiency and mminimises waste in resource planning for construction projects.			

Article 31	Title: A System Proposal for Information Management in Building Sector Based on BIM, SSI, IoT and Blockchain		
Year: 2022	Data types:	Data management:	Data conversion:
Cocco et al. [112]	IoT	External	Algorithm based
Description: This work outlines a framework that integrates BIM, Self-Sovereign Identity (SSI), the Internet of Things (IoT), and Blockchain to enhance information management in the construction sector. The system leverages blockchain to ensure data transparency, security, and auditability throughout a building's lifecycle, storing all relevant information in decentralised databases. BIM files and IoT-generated data are securely stored and linked to a building's digital identity, allowing for seamless data verification and transfer between stakeholders. This approach mitigates risks of fraud and manipulation, providing a robust, verifiable record of all building-related activities.			

Article 32	Title: Directed Representative Graph Modeling of MEP Systems Using BIM Data		
Year: 2022	Data types:	Data management:	Data conversion:
Han et al. [56]	Spatial	Internal	Graph based
Description: The study proposes a novel method for creating a graph-based model to represent MEP systems using data from BIM. The approach involves extracting representative points and edges from MEP elements, converting them into triangular meshes, and then defining the directional flow between system components. The method also integrates IFC to ensure accurate topological connections. The model is designed to support intelligent monitoring and management of MEP systems by integrating with IoT, enabling real-time analysis of system performance, flow directions, and potential issues like leaks or malfunctions			

Article 33	Title: UAS-BIM based Real-time Hazard Identification and Safety Monitoring of Construction Projects		
A Year: 2017	Data types:	Data management:	Data conversion:
Alizadehsalehi et al. [116]	IoT	Internal	Algorithm based
Description: This work explores a framework integrating Unmanned Aerial Systems (UAS) and BIM to enhance construction site safety monitoring. The approach uses drones equipped with sensors to capture real-time data on-site, which is then processed within a BIM environment to identify potential hazards such as fall risks or structural weaknesses. This integration allows for continuous safety monitoring and the automation of hazard identification, significantly improving response times and overall safety management in construction projects.			

Article 34	Title: Optimizing energy efficiency in operating built environment assets through building information modeling: A case study		
Year: 2017	Data types:	Data management:	Data conversion:
Petri et al. [55]	Environmental	External	Algorithm based
Description: This work examines how BIM can be leveraged to improve energy efficiency in the operational phase of built assets. The study emphasises the use of BIM as a tool for optimiszing energy-related decisions throughout the entire building lifecycle. This work focuses on reducing carbon emissions and improving sustainability. It demonstrates a methodology developed during the European research project "Sporte2" and presents the application of BIM for energy optimisation, emphasising waste and emission reduction in both construction and operation phases. The case study emphasises BIM's role in achieving energy efficiency targets by minimising the performance gap, enhancing in-use energy efficiency, and integrating supply chain processes. Additionally, the research suggests training directions for BIM usage to further enhance building energy optimization.			

Article 35	Title: Deep learning based approaches from semantic point clouds to semantic BIM models for heritage digital twin		
A Year: 2024	Data types:	Data management:	Data conversion:
Pan et al. [71]	Spatial	Internal	Algorithm based
Description: This work explores the use of deep learning techniques to transform point cloud data into BIM for cultural heritage preservation. It focuses on Taoping Village, a heritage site in China, using data captured from unmanned aerial vehicles (UAV) and terrestrial laser scanning (TLS). The study highlights the use of a KP-SG neural network, which efficiently segments point clouds into categories like buildings and vegetation, achieving high accuracy in the process. This methodology enables the creation of detailed semantic BIM models, which are critical for analysing and preserving heritage sites, while also integrating these models into a digital twin platform for real-time monitoring and visualisation.The approach demonstrates how deep learning can automate processes that were traditionally manual, offering significant advancements in preserving and understanding heritage architecture through digital twins.			

Article 36	Title: BIM-based life cycle assessment for different structural system scenarios of a residential building		
Year: 2022	Data types:	Data management:	Data conversion:
Morsi et al. [130]	Cost	Internal	Existing standard
Description: This work evaluates the environmental impact of various structural systems using an integrated approach combining BIM and Life Cycle Assessment (LCA). The study compares three structural systems including reinforced concrete solid slab, composite systems, and steel. Each system's environmental impact is assessed across different life cycle stages, including construction, operation, and demolition. The findings suggest that the operational phase, especially for steel structural systems, has the highest environmental impact. Slabs, beams, and reinforced concrete elements contribute significantly to this impact. The research emphasises the need to focus on sustainable material selection and design strategies to reduce environmental burdens throughout the building's lifecycle.			

Article 37	Title: LiDAR-Based Automatic Pavement Distress Detection and Management Using Deep Learning and BIM		
Year: 2024	Data types:	Data management:	Data conversion:
Tan et al. [72]	Spatial	External	Algorithm based
Description: This work explores the integration of LiDAR, deep learning, and BIM to automate the detection and management of pavement distress. The system employs LiDAR data to capture detailed road surface conditions and uses deep learning algorithms to identify and classify pavement issues like cracks, potholes, and other defects. This process is then linked with BIM for improved management and predictive maintenance. By leveraging LiDAR's precision and deep learning's pattern recognition, the system enhances both the accuracy and speed of pavement condition assessments. This approach can significantly reduce manual inspection efforts and improve the lifecycle management of road infrastructure.			

Article 38	Title: A method for transferring BIM data into domain ontologies: A case study based on airport services		
Year: 2022	Data types:	Data management:	Data conversion:
Herrera-Martin et al. [134]	Facility management	Internal	Ontology based
Description: This work explores a framework for converting BIM data into domain-specific ontologies, particularly for airport operations. The approach leverages ontological mappings to enhance data interoperability and automate knowledge transfer, enabling more effective management of airport facilities. The case study illustrates how BIM data can be semantically enriched and utilized to improve decision-making processes in airport services.			

Article 39	Title: Optimising Embodied Energy and Thermal Performance of Thermal Insulation in Building Envelopes via an Automated Building Information Modelling (BIM) Tool		
Year: 2020	Data types:	Data management:	Data conversion:
Chen et al. [120]	Environmental	Internal	Algorithm based
Description: This work presents a BIM-integrated approach to optimising the insulation of building envelopes, which includes floors, roofs, and external walls. It utilises tools such as Revit and Dynamo to balance the trade-offs between embodied energy and thermal performance. The study highlights how small improvements in thermal performance can drastically increase embodied energy, by over 50 times in some cases. This framework was tested on a case study in Sydney, demonstrating the benefits of multi-objective optimization for making informed decisions about insulation materials and their thickness			

Article 40	Title: Pavement condition information modelling in an I-BIM environment		
Year: 2022	Data types:	Data management:	Data conversion:
Bosurgi et al. [135]	Facility management	External	Algorithm based
Description: This work proposes a framework that integrates pavement condition data into an Infrastructure-BIM (I-BIM) environment. This approach improves the visualization and management of pavement survey data, facilitating better decision-making in road maintenance. The method uses smart objects and 3D modelling to represent structural and functional pavement conditions, creating a more user-friendly tool for managing infrastructure lifecycles. Tested on a motorway, the solution demonstrated effective results for simplifying pavement management.			

Article 41	Title: A Framework for the inclusion of RF transparency parameters into BIM databases		
Year: 2019	Data types:	Data management:	Data conversion:
Caldeirinha et al. [136]	Facility management	External	Algorithm based
Description: This study introduces a method for integrating radiofrequency (RF) transparency data into BIM systems. With the increasing deployment of 5G and other radio-based services, understanding how radio waves propagate within buildings is critical. The framework introduces a multilayer electromagnetic simulation tool designed to evaluate the RF transparency of building materials, with the goal of optimizing indoor radio coverage while addressing safety considerations. This integration into BIM would enhance visualization and management of radio coverage in buildings.			

Article 42	Title: Bim-enabled facility management optimization based on post-occupancy evaluations and building monitoring: Framework and first results		
Year: 2020	Data types:	Data management:	Data conversion:
Seghezzi et al. [137]	Facility management	Internal	Algorithm based
Description: This work outlines a framework for optimising facility management with BIM, sensor data, and post-occupancy evaluations (POEs). The system uses real-time data from building sensors to monitor aspects like air quality, occupancy, and energy usage, while also incorporating user feedback through surveys. These inputs help adjust cleaning protocols, resource allocation, and maintenance activities to improve building performance and occupant satisfaction. Additionally, the study explores how integrating blockchain technology with BIM can automate facility management tasks, such as service payments through smart contracts			

Article 43	Title: Exchanging Progress Information Using IFC-Based BIM for Automated Progress Monitoring		
Year: 2023	Data types:	Data management:	Data conversion:
Sheik et al. [105]	Scheduling	Internal	Algorithm based
Description: This work explores a framework for integrating IFC-based BIM models with construction progress monitoring. This methodology involves four key stages: defining IFC entities, enriching these entities with progress-related data, regularly updating the model with actual progress from the construction site, and visualizing progress through color-coded 3D models and reports. The approach aims to improve accuracy and collaboration in construction management by automating the update of progress data, such as schedules, costs, and other key performance indicators. It also addresses the limitations of earlier methods, which focused primarily on time-related data, by leveraging the latest IFC4.x schema, offering a comprehensive solution for progress tracking and reporting.			

Article 44	Title: A Building Information Modeling Approach to Integrate Geomatic Data for the Documentation and Preservation of Cultural Heritage		
Year: 2020	Data types:	Data management:	Data conversion:
Solla et al. [73]	Spatial	Internal	Algorithm based
Description: This work discusses the integration of non-destructive testing (NDT) techniques with BIM for the preservation of historic buildings. The study focuses on incorporating data from techniques such as terrestrial laser scanning, ground-penetrating radar, and infrared thermography, combined with aerial imaging via unmanned aircraft systems (UAS), into a BIM environment. To document and assess its structural features and issues for future restoration efforts, this approach was applied at the Monastery of Batalha, a UNESCO World Heritage site in Portugal. The goal is to optimise data integration for use in facility management, restoration, and cultural research.			

Article 45	Title: Cash flow system development framework within integrated project delivery (IPD) using BIM tools		
Year: 2021	Data types:	Data management:	Data conversion:
Elghaish et al. [106]	Cost, scheduling	Internal	Algorithm based
Description: This paper introduces a framework for enhancing cash flow management in construction projects by combining BIM with the IPD methodology. This approach leverages the collaborative nature of IPD, which involves early stakeholder participation and shared risks and rewards. The framework utilises 4D and 5D BIM to automate cash flow projections, combining time (4D) and cost (5D) data to generate more accurate financial forecasts throughout the project's lifecycle. The study addresses common challenges like the alignment of cost structures and schedules, proposing a methodology that enhances transparency and efficiency in project cost management. By testing this framework on a real-world case study, the authors demonstrated how integrating BIM tools within IPD can streamline cash flow management and lead to better financial outcomes for all project participants			

Article 46	Title: Integrating BIM Processes with LEED Certification: A Comprehensive Framework for Sustainable Building Design		
Year: 2023	Data types:	Data management:	Data conversion:
Di Gaetano et al. [121]	Environmental	External	Existing standard
Description: This work outlines a structured framework for aligning BIM with the LEED certification system, specifically focusing on the LEED v4.1 "Building Design + Construction" category. The study emphasises integrating sustainability goals at the early design stages through customised BIM-LEED worksheets. These worksheets guide the project team through LEED prerequisites and credit requirements, ensuring that key BIM applications are effectively used throughout the project lifecycle. Additionally, the research explores the role of "Pilot Credits" and "Regional Priority Credits" to enhance a project's sustainability profile and optimise LEED certification outcomes. This framework facilitates the seamless integration of BIM processes, aiding architects and engineers in proactively addressing sustainability challenges while aiming for high levels of LEED certification.			

Article 47	Title: BIM-oriented indoor network model for indoor and outdoor combined route planning		
Year: 2016	Data types:	Data management:	Data conversion:
Teo and Cho [74]	Spatial	External	Algorithm based
Description: This work presents a multi-purpose geometric network model (MGNM) that integrates BIM and GIS for indoor and outdoor route planning. Proposed model extracts and processes data from IFC and uses an entrance-to-street strategy to connect networks. This allows for more accurate route planning, particularly useful in emergency response scenarios, with enhanced precision and reduced computational time compared to traditional methods			

Article 48	Title: BIM-based Cultural Heritage Asset Management Tool. Innovative Solution to Orient the Preservation and Valorization of Historic Buildings		
Year: 2021	Data types:	Data management:	Data conversion:
Piaia et al. [138]	Facility management	External	Existing standard
Description: This study investigates a tool developed to enhance the management and preservation of cultural heritage assets. This tool leverages BIM technology to streamline the condition assessment and maintenance of historical buildings. It integrates data gathered through BIM to support on-site inspections, optimising conservation planning according to various preservation needs. Developed as part of the H2020-INCEPTION project, the tool aims to support decision-making in restoration and asset management by providing a user-friendly system that enhances the quality and efficiency of building inspections, facilitating long-term preservation efforts			

Article 49	Title: Automatic gbXML Modeling from LiDAR Data for Energy Studies		
Year: 2020	Data types:	Data management:	Data conversion:
Otero et al. [75]	Spatial, environmental	External	Algorithm based
Description: This work introduces a streamlined method for generating BIM in the gbXML format, using point cloud data obtained from mobile LiDAR scanners. The main purpose of this procedure is to facilitate energy analysis by enabling faster and more accurate 3D modelling of buildings, particularly for energy efficiency studies. The approach is designed for non-specialists in 3D modelling, making it accessible to energy professionals through semi-automated tools. This method significantly reduces the time required to model complex point clouds, completing tasks in less than 10 min while maintaining a high level of precision. The paper highlights the system's application in real-world scenarios and compares its performance against traditional manual modelling methods, demonstrating its efficiency for energy analysis in buildings.			

Article 50	Title: Smart Progress Monitoring Framework for Building Construction Elements Using Videography–MATLAB–BIM Integration		
Year: 2021	Data types:	Data management:	Data conversion:
Arif and Khan [107]	Scheduling	External	Algorithm based
Description: This work presents a method for automating construction progress tracking. It integrates videography, MATLAB for image processing, and BIM to create a real-time framework for monitoring the progress of building elements. The system utilisses on-site video data, processed through MATLAB algorithms, to compare as-built conditions with the BIM model, offering a cost-effective and efficient solution for monitoring construction progress. This framework aims to improve accuracy and reduce manual inspections in construction management.			

Article 51	Title: From Sketching to BIM Workflow for the Generation of IFC-based BIM Models from 4D Semantic Sketches		
Year: 2023	Data types:	Data management:	Data conversion:
Stauss et al. [76]	Spatial	Internal	Algorithm based
Description: This work presents a workflow that transitions from conceptual design sketches to BIM using IFC. It leverages machine learning to process 4D semantic sketches, converting them into conceptual BIM models in a way that preserves information accuracy throughout a project's lifecycle. The key contribution of this research is the seamless integration of artificial intelligence and BIM, enabling more flexible and efficient design processes, especially in the early conceptual stages.			

Article 52	Title: BIM-SLAM: Integrating BIM Models in Multi-session SLAM for Lifelong Mapping using 3D LiDAR		
Year: 2023	Data types:	Data management:	Data conversion:
Vega Torres et al. [77]	Spatial	External	Algorithm based
Description: This work focuses on combining BIM with Simultaneous Localization and Mapping (SLAM) to improve long-term mapping in indoor environments where GPS is unavailable. It leverages 3D LiDAR data collected over multiple sessions and integrates it with existing BIM models to create updated and accurate maps of indoor spaces. The key contribution is the methodology for using BIM to enhance the accuracy and reliability of SLAM in complex environments, providing an ongoing mapping solution for dynamic indoor settings			

Article 53	Title: Supporting post-occupant evaluation through work order evaluation and visualization in FM-BIM		
Year: 2018	Data types:	Data management:	Data conversion:
Pin et al. [132]	Facility management	Internal	Algorithm based
Description: This work explores how BIM can be integrated with facility management (FM) systems to improve post-occupant evaluations. By analysing data from work orders, the system helps visualise patterns in occupant complaints and facility issues at both building and cluster levels. This real-time data analysis enables facility managers to identify priority areas, optimize building performance, and enhance occupant satisfaction through targeted maintenance and operational decisions			

Article 54	Title: Integrating work sequences and temporary structures into safety planning: Automated scaffolding-related safety hazard identification and prevention in BIM		
Year: 2016	Data types:	Data management:	Data conversion:
Kim et al. [78]	Spatial, scheduling	External	Existing standard
Description: This study focuses on enhancing safety in construction by integrating scaffolding and temporary structures into BIM. The research presents an automated platform that uses algorithms to detect safety hazards related to scaffolding activities during construction. By visualising work sequences and spatial movements of workers, the system enables proactive safety planning and communication, reducing the likelihood of accidents. This automated approach improves the identification of hazards that manual inspections often overlook, providing a significant advancement in construction safety			

Article 55	Title: Low-cost mobile augmented reality service for building information modeling		
Year: 2023	Data types:	Data management:	Data conversion:
Um et al. [79]	Spatial	External	Algorithm based
Description: The study focuses on developing an affordable AR tool that integrates with BIM to enhance decision-making and workflow efficiency in construction. The research demonstrates the usability of the service through a prototype applied to pipe maintenance, showcasing how AR can support on-site inspections, workflow management, and data reduction. It emphasises the need for accessible digital solutions for smaller organisations in the construction sector, promoting digitalisation without the high costs typically associated with advanced technologies. This service allows operators to visualise 3D BIM models in real-time using mobile devices, making it a practical tool for improving site management and maintenance operations. The integration of BIM server and building automation tools further enhances data integration and decision-making during construction activities.			

Article 56	Title: Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy		
Year: 2019	Data types:	Data management:	Data conversion:
Akanbi et al. [122]	Environmental, cost	External	Existing standard
Description: This work focuses on integrating end-of-life performance assessments into building designs to support circular economy principles. It uses BIM tools like Revit to analyse life-cycle performance, deconstruction efficiency, and design adaptability for disassembly. The system contributes by offering a decision-support tool for planners and government agencies, ensuring building designs facilitate efficient material recovery and compliance with sustainability goals			

Article 57	Title: Mapping private, common, and exclusive common spaces in buildings from BIM/IFC to LADM. A case study from Saudi Arabia		
Year: 2021	Data types:	Data management:	Data conversion:
Alattas et al. [80]	Spatial	Internal	Algorithm based
Description: This work explores the integration of BIM and IFC with the Land Administration Domain Model (LADM) for better 3D cadastral registration in Saudi Arabia. The study focuses on the classification of various space types, including private, common, and exclusive common spaces, and their legal registration within multi-owner buildings, using IFC files to represent geometric and spatial details. The research aims to bridge the gap between architectural/engineering designs and legal land administration, ensuring smoother transitions from design to legal registration			

Article 58	Title: Development of driving simulation scenarios based on building information modeling (BIM) for road safety analysis		
Year: 2021	Data types:	Data management:	Data conversion:
Dols et al. [81]	Spatial	Internal	Algorithm based
Description: This work focuses on creating virtual driving simulations using BIM data to enhance road safety evaluations. By utilising an IFC file format, the study demonstrates how BIM can streamline the design of driving scenarios, significantly reducing editing and programming time. The research highlights how this method improves cost-efficiency and the effectiveness of road safety audits by allowing for more precise and rapid scenario development compared to conventional techniques			

Article 59	Title: Towards design process validation integrating graph theory into BIM		
Year: 2017	Data types:	Data management:	Data conversion:
Donato [82]	Spatial	External	Graph based
Description: This work explores the application of graph theory to enhance the architectural design process using BIM. It focuses on evaluating alternative design solutions by analysing circulation spaces within a building. The method involves converting spatial relationships from a BIM model into a topology graph, which is then mathematically analysed using tools like MATLAB to support decision-making during the early design stages. The study emphasises how this integration helps architects make data-driven choices to optimize layouts, particularly for circulation and space efficiency			

Article 60	Title: Automated facility inspection using robotics and BIM: A knowledge-driven approach		
Year: 2023	Data types:	Data management:	Data conversion:
Chen et al. [139]	Facility management	External	Ontology based
Description: This work explores how robotics, combined with BIM, can automate the traditionally labor-intensive process of facility inspection. The study introduces a knowledge-driven model called iSTA (Integrated Scene-Task-Agent) that leverages both explicit knowledge from BIM models and tacit human expertise to guide robots in navigating complex environments for autonomous inspections. This system aims to enhance inspection efficiency, particularly in challenging environments, by using robotics for tasks that typically require human presence.			

Article 61	Title: A real-time construction safety monitoring system for hazardous gas integrating wireless sensor network and building information modeling technologies		
Year: 2018	Data types:	Data management:	Data conversion:
Cheung et al. [117]	IoT	External	Algorithm based
Description: This work explores the development of an advanced system combining Wireless Sensor Networks (WSNs) and BIM to enhance safety on construction sites. The system employs sensors to track environmental conditions like temperature and humidity, as well as monitor hazardous gas levels. When dangerous levels are detected, the system triggers automated alarms and ventilation to mitigate risks. The integration of BIM allows for real-time visual representation of safety data, improving decision-making and response efficiency. A case study demonstrates the system's effectiveness in improving safety management in confined or hazardous environments			

Article 62	Title: Data sharing for sustainable building assessment		
Year: 2012	Data types:	Data management:	Data conversion:
Biswas and Krishnamurti [123]	Environmental	External	Existing standard
Description: This work focuses on the integration of data sharing methods in sustainable building evaluation, particularly using BIM for effective collaboration. By linking BIM with sustainability assessment tools like LEED, the research demonstrates how automated data exchange can streamline the process of evaluating a building's environmental performance. This approach helps minimise project costs, improves decision-making, and supports the achievement of certifications by leveraging interoperable system.			

Article 63	Title: BIM-based augmented reality inspection and maintenance of fire safety equipment		
Year: 2020	Data types:	Data management:	Data conversion:
Chen et al. [140]	Facility management	External	Algorithm based
Description: This work discusses the integration of BIM with AR to enhance the inspection and maintenance processes of fire safety systems. This approach utilises AR to overlay critical information about fire safety equipment directly onto physical environments, allowing inspectors to view real-time data and 3D visualizations of equipment through mobile devices. The system improves accuracy and efficiency in identifying potential issues and ensuring compliance with fire safety regulations. It also simplifies access to maintenance history and operational guidelines, ensuring that fire safety equipment is regularly inspected and maintained			

Article 64	Title: Development of formwork automation design software for improving construction productivity		
Year: 2021	Data types:	Data management:	Data conversion:
Lee et al. [83]	Spatial	External	Algorithm based
Description: This work focuses on creating a software tool that automates the design and layout of formwork in construction projects. The software uses 3D BIM data derived from 2D CAD drawings to generate formwork designs, reducing manual effort and potential human error in planning. The system improves efficiency by automatically calculating formwork quantities and types, though the current version has limitations in handling complex layouts and requires further algorithmic development to enhance its accuracy and automation. This tool is particularly useful for large-scale projects, where formwork design plays a critical role in overall productivity, cost, and safety. By integrating the software with aluminum formwork libraries, the study demonstrates its potential to streamline construction processes.			

Article 65	Title: Development of a building information model-guided post-earthquake building inspection framework using 3D synthetic environments		
Year: 2023	Data types:	Data management:	Data conversion:
Levine et al. [141]	Facility management	External	Algorithm based
Description: This study introduces an automated framework that utilises BIM and computer vision to improve post-earthquake inspections. The framework employs unmanned aerial vehicles (UAVs) to collect images of damaged buildings, which are then analysed using deep learning algorithms to detect and localise damage. By integrating these images with BIM data, the system can assess the damage's impact on specific structural components. This automated process enhances the accuracy and efficiency of building inspections, allowing for rapid safety assessments and faster community recovery after seismic events			

Article 66	Title: A non-centralized adaptive method for dynamic planning of construction components storage areas		
Year: 2019	Data types:	Data management:	Data conversion:
Li et al. [84]	Spatial	External	Algorithm based
Description: This work presents a flexible and decentralised approach to managing storage areas on construction sites. This method adapts to the real-time availability of space and changing demands for materials, improving efficiency in environments with limited storage capacity. The site detail features are extracted from BIM model to provide basic information. By using real-time spatial recognition and genetic algorithms, the system dynamically allocates space based on current construction activities and material supply.			

Article 67	Title: Development of a Web Application for Historical Building Management through BIM Technology		
Year: 2019	Data types:	Data management:	Data conversion:
Rodrigues et al. [142]	Facility management	External	Algorithm based
Description: This study describes a system developed to assist in the maintenance and preservation of historical buildings by integrating BIM with a web-based management platform. This system allows for the digitisation and organisation of building data, facilitating easier access to documentation such as drawings, inspection reports, and specifications. The application uses Autodesk Revit to model historical buildings, stores data in Microsoft SQL Server, and interacts with users via an API developed in C#. This approach enhances efficiency in managing heritage sites by streamlining data collection, reducing information loss, and improving long-term maintenance strategies.			

Article 68	Title: BIM-based mixed-reality application for bridge inspection and maintenance		
Year: 2022	Data types:	Data management:	Data conversion:
Nguyen et al. [108]	Facility management, Scheduling	External	Algorithm based
Description: This work focuses on the integration of BIM with mixed reality (MR) technologies to improve the inspection and maintenance of bridges. This system utilises Microsoft HoloLens and other MR devices to overlay BIM data directly onto real-world bridge structures during inspections. It enhances decision-making by allowing inspectors to interact with 3D models, visualise structural conditions, and map damage more effectively while working remotely from the office. This innovative approach reduces the need for on-site presence and streamlines the management of bridge maintenance, increasing both efficiency and accuracy.			

Article 69	Title: Comparative Analysis of Resource and Climate Footprints for Different Heating Systems in Building Information Modeling		
Year: 2022	Data types:	Data management:	Data conversion:
Sameer et al. [124]	Environmental	Internal	Existing standard
Description: This work evaluates the environmental impacts of various heating systems using BIM for a case study in Germany. The systems evaluated consist of a gas condensing boiler, ground-source heat pumps (GSHP), and GSHP combined with photovoltaic (PV) systems. The study measures the climate, material, energy, land, and water footprints of these systems.			

Article 70	Title: Enhancing the level of confidence in the safe fire evacuation operation employing a combination of BIM and fuzzy TOPSIS method		
Year: 2023	Data types:	Data management:	Data conversion:
Soltaninejad et al. [85]	Spatial	External	Graph based
Description: This work proposes a hybrid approach to improve fire evacuation safety in buildings. By integrating BIM with the fuzzy TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) method, the study aims to optimise evacuation routes and decision-making processes during emergencies. The model analyses various evacuation scenarios, using BIM to provide real-time data on building layouts, while fuzzy TOPSIS evaluates and ranks potential evacuation routes based on safety criteria. This approach increases confidence in evacuation plans by reducing hazards and optimizing response times for both occupants and rescue teams.			

Article 71	Title: A building information modeling-based tool for estimating building demolition waste and evaluating its environmental impacts		
Year: 2021	Data types:	Data management:	Data conversion:
Su et al. [125]	Environmental	External	Algorithm based
Description: This work focuses on developing a system that integrates BIM, LCA, and GIS to estimate and assess the environmental impact of building demolition waste. BIM is used to model the building's geometry and characteristics, GIS designs optimal waste transportation routes, and LCA evaluates environmental damage, including resource depletion. This tool automates waste quantification and impact evaluation at the design stage, aiming to enhance waste management and sustainability in construction projects.			

Article 72	Title: Parametric Performance Analysis of the Cooling Potential of Earth-to-Air Heat Exchangers in Hot and Humid Climates		
Year: 2022	Data types:	Data management:	Data conversion:
Bughio et al. [86]	Spatial, environmental	External	Algorithm based
Description: This work evaluates how EAHE systems can be optimised for passive cooling in buildings by leveraging ground temperatures. The study uses dynamic computer simulations to assess various parameters like pipe layout, installation depth, and air flow rate, which significantly affect the cooling performance. BIM is used to provide spatial features for simulations.			

Article 73	Title: TLS measurements of initial imperfections of steel frames for structural analysis within BIM-enabled platforms		
Year: 2021	Data types:	Data management:	Data conversion:
Chacón et al. [87]	Spatial	Internal	Algorithm based
Description: This work explores how Terrestrial Laser Scanning (TLS) technology can be applied to measure geometric imperfections in steel frames. These imperfections, often present in real-world construction, are captured as 3D point cloud data. The study integrates this data into BIM platforms to develop realistic wire models of steel frames, which can then be used for further structural analysis. This method allows for accurate representation of "as-built" conditions and supports nonlinear geometric analysis, improving the precision of structural verification and maintenance in BIM environments.			

Article 74	Title: Building Information Modeling (BIM) Enabled Facilities Management Using Hadoop Architecture		
Year: 2017	Data types:	Data management:	Data conversion:
Arslan et al. [143]	Facility management	External	Algorithm based
Description: This study discusses how BIM can be integrated with Hadoop's big data capabilities to enhance facilities management (FM). The study introduces a system that leverages BIM and wireless sensor networks to monitor facility conditions, such as safety and environmental hazards, by collecting vast amounts of data. By using Hadoop's distributed storage and processing power, the system can efficiently handle large volumes of sensor data, providing real-time insights and visualizations for facility managers. This setup helps streamline FM processes, particularly in enhancing safety and operational efficiency.			

Article 75	Title: Application of Vision-Based Artificial Intelligence in Creating a Contactless Interaction with Immersive Environments		
Year: 2022	Data types:	Data management:	Data conversion:
Ramaji et al. [88]	Spatial	Internal	Algorithm based
Description: This work explores how vision-based AI technology is used to enable users to interact with virtual environments acquired from BIM model without physical touch. The study develops a system where body movements and gestures are captured and mapped to commands in virtual reality (VR) systems, allowing for a seamless, hands-free interaction. This approach leverages AI to enhance user experience in immersive environments, such as in architecture or gaming, where natural and intuitive interaction with virtual objects is essential for improving usability and reducing barriers to engagement.			

Article 76	Title: Localization of RFID-equipped assets during the operation phase of facilities		
Year: 2013	Data types:	Data management:	Data conversion:
Motamedi et al. [118]	Facility management, IoT	Internal	Algorithm based
Description: This work explores the use of RFID technology to track and manage assets within indoor environments, particularly during a building's operation phase. The system uses RFID tags attached to assets, with location data integrated into BIM. The location of both fixed and movable assets can be tracked in real time, enabling facilities managers to efficiently locate and manage equipment without needing a Real-Time Location System (RTLS). The approach employs pattern matching and clustering algorithms to estimate asset locations based on received signal strength and spatial constraints, improving operational efficiency in facilities management.			

Article 77	Title: Using LADM and BIM for property and tourist taxation in the municipality of Bar, Montenegro		
Year: 2023	Data types:	Data management:	Data conversion:
Radulović et al. [89]	Spatial, cost	External	Algorithm based
Description: This work investigates how the Land Administration Domain Model (LADM) and BIM can improve the accuracy and efficiency of property and tourist tax calculations. The study proposes integrating BIM models with municipal tax databases to automate tax assessments based on building data such as area, construction quality, and facilities (e.g., windows, rooms, installations). This approach enhances transparency and equity in tax collection by reducing manual input errors and ensuring data consistency from design to operation phases.			

Article 78	Title: Integrating BIM and Multiple Construction Monitoring Technologies for Acquisition of Project Status Information		
Year: 2023	Data types:	Data management:	Data conversion:
Hasan and Sacks [90]	Scheduling, spatial	External	Algorithm based
Description: The study explores the integration of BIM with various construction monitoring technologies to improve real-time tracking of project progress. The research highlights the use of 3D sensing technologies such as LiDAR, UAVs, and wireless sensors to capture as-built data, which is then compared to the planned BIM models for enhanced project status evaluation. This approach enables more precise progress monitoring, automating processes like clash detection, and improving decision-making through real-time data integration. The study emphasizes how these combined technologies increase accuracy, reduce manual labour, and provide better insight into the construction process.			

Article 79	Title: Design Cost Analysis in a BIM/VPI Framework		
Year: 2023	Data types:	Data management:	Data conversion:
Jorge et al. [131]	Cost	External	Algorithm based
Description: This work explores the integration of BIM with Virtual Prototyping and Integration (VPI) to assess the financial feasibility of design alternatives. It examines how BIM enhances cost management by automating cost calculations through detailed building models, which contain comprehensive information about materials, labour, and other cost factors. By linking design iterations with cost data, the framework supports architects and engineers in balancing design quality with financial constraints, improving decision-making early in the project lifecycle.			

Article 80	Title: BIM-integrated thermal analysis and building energy modeling in 3D-printed residential buildings		
Year: 2023	Data types:	Data management:	Data conversion:
Kamel and Kazemian [126]	Environmental	Internal	Existing standard
Description: The work focuses on how BIM can be integrated with BEM to analyse and improve the energy performance of 3D-printed residential structures. The study evaluates different construction materials and climate zones, using BIM to simulate energy consumption and thermal behaviour, particularly in 3D-printed buildings, which often use lightweight concrete and other innovative materials. By leveraging BIM, the workflow improves the accuracy of energy simulations and supports more efficient design iterations, enhancing sustainability in 3D-printed housing. This approach helps architects and engineers to optimize energy efficiency during the early design stages by modelling various scenarios and materials, facilitating the creation of low-energy, sustainable residential buildings.			

Article 81	Title: Developing a BIM Single Source of Truth Prototype Using Blockchain Technology		
Year: 2023	Data types:	Data management:	Data conversion:
Hijazi et al. [91]	All types available	Internal	Algorithm based
Description: This work explores the integration of blockchain with BIM to create a reliable, transparent, and secure data management system for construction projects. The study presents a prototype that demonstrates how blockchain can be used to establish a single source of truth (SSoT) for managing construction supply chain data, focusing on improving transparency and data exchange among stakeholders. The framework provides secure, immutable records of transactions and project updates, enhancing trust and collaboration across the construction lifecycle.			

Article 82	Title: The Building Information Modeling and Its Use for Data Transformation in the Structural Design Stage		
Year: 2016	Data types:	Data management:	Data conversion:
Liu et al. [92]	Spatial	External	Algorithm based
Description: This work examines how BIM supports the efficient transformation of design data into structural models. It highlights the integration of BIM with structural analysis tools, streamlining workflows by automating data exchange between architectural models and engineering calculations. This process helps reduce errors and improves collaboration during the structural design phase, facilitating better decision-making and coordination in construction projects			

Article 83	Title: A Simplified Framework to Integrate Databases with Building Information Modeling for Building Energy Assessment in Multi-Climate Zones		
Year: 2024	Data types:	Data management:	Data conversion:
Lobos Calquin et al. [97]	Environmental, weather	External	Existing Standard
Description: This study introduces a method for integrating BIM with environmental assessment databases to improve energy performance evaluations across different climate zones. This framework automates data exchange. Especially between BIM and Building Environmental Assessment Methods (BEAM), such as LEED or BREEAM, streamlining energy certification processes. The system utilises database connections and BIM programming to improve the accuracy of energy assessments, with a specific emphasis on addressing the complex requirements of multi-climate zones, such as those in Chile.			

Article 84	Title: Translating building information modeling to building energy modeling using model view definition		
Year: 2014	Data types:	Data management:	Data conversion:
Jeong et al. [93]	Spatial, environmental	External	Existing Standard
Description: This work presents a method that streamlines the conversion of BIM data to BEM using Model View Definition (MVD). This approach enables seamless translation of building geometry, materials, and topology from BIM to energy models. By using an intermediate class package and automating data transfer through tools like Revit2Modelica, the framework minimises data loss and enhances the efficiency of energy simulations. This system improves interoperability and simplifies energy analysis during design			

Article 85	Title: BIM-based automated construction waste estimation algorithms: The case of concrete and drywall waste streams		
Year: 2019	Data types:	Data management:	Data conversion:
Guerra et al. [128]	Environmental	Internal	Algorithm based
Description: This work focuses on developing algorithms to estimate construction waste generated during the building process. These algorithms utilise BIM to automate the quantification of waste in real-time, particularly for concrete and drywall. By comparing the amount of material purchased versus what is incorporated into the building, the algorithms calculate waste percentages and offer insights into minimising material overuse and inefficiencies. The study highlights that the integration of BIM allows for more accurate waste management and supports decision-making at early design stages, contributing to more sustainable construction practices. These methods can help reduce costs and environmental impact by optimizing resource use and minimizing waste.			

Article 86	Title: Mapping actual thermal properties to building elements in gbXML-based BIM for reliable building energy performance modeling		
Year: 2015	Data types:	Data management:	Data conversion:
Ham and Golparvar-Fard [127]	Environmental	External	Existing standard
Description: The study focuses on improving the accuracy of energy performance simulations by associating real-world thermal properties incorporating building elements within a BIM environment. The study employs the gbXML schema, which is commonly used for transferring BIM data to energy modelling tools. It introduces an automated method for updating and mapping measured thermal properties (like conductivity and thermal resistance) to their corresponding building components within the model, ensuring that the energy simulation reflects actual building conditions rather than default or assumed values.			

Article 87	Title: Sustainability-based lifecycle management for bridge infrastructure using 6D BIM		
Year: 2020	Data types:	Data management:	Data conversion:
Kaewunruen et al. [109]	Environmental, scheduling, cost	Internal	Algorithm based
Description: This work introduces an innovative approach to manage the lifecycle of bridge infrastructure, using the Donggou Bridge as a case study. It leverages 6D BIM, combining 3D modeling with time schedules, cost projections, and carbon footprint assessments to analyse sustainability across the entire lifecycle of the bridge. This research highlights the benefits of early-stage BIM development, enabling enhanced collaboration among stakeholders and improving efficiency in construction, maintenance, and sustainability outcomes			

Article 88	Title: BIM-based object mapping using invariant signatures of AEC objects		
Year: 2023	Data types:	Data management:	Data conversion:
Li et al. [94]	Spatial	External	Algorithm based
Description: This study explores a method for improving interoperability and automation in BIM workflows by using invariant signatures of AEC objects. These invariant signatures are intrinsic properties of objects that remain consistent across different software and project environments, enabling more reliable mapping and classification of BIM components. The framework was tested using models from various sources, demonstrating its potential to enhance BIM tasks such as quantity take-off and structural analysis.			

Article 89	Title: Graph-Based methodology for multi-scale generation of energy analysis models from IFC		
Year: 2023	Data types:	Data management:	Data conversion:
Mediavilla et al. [54]	Spatial	External	Graph based
Description: This work presents a novel approach to automate the generation of BEM from BIM. This method leverages graph algorithms to map and transform BIM data, particularly using IFC standards, ensuring that spatial and relational data are accurately represented. The methodology's multi-scale approach enables it to accommodate different levels of detail, ranging from individual elements to entire complexes, offering great flexibility for conducting energy analysis at various building scales. This approach is especially beneficial in retrofitting scenarios, where it simplifies the energy modelling process and reduces the complexity of input data requirements.			

Article 90	Title: Toward cognitive digital twins using a BIM-GIS asset management system for a diffused university		
Year: 2022 Meschini et al. [101]	Data types: GIS	Data management: Internal	Data conversion: Algorithm based
Description: This work explores the integration of BIM and GIS to develop an asset management system (AMS) for the operation and maintenance of university campuses. This research focuses on creating Cognitive Digital Twins (CDTs), which allow buildings to autonomously react to environmental changes, enhancing decision-making in both routine operations and emergency scenarios. A prototype was demonstrated using buildings from the University of Turin, where real-time data visualisation and crowd simulations were used to improve safety measures. Future directions include incorporating AI and IoT to further optimise building performance and management.			

Article 91	Title: Digitalization of culturally significant buildings: ensuring high-quality data exchanges in the heritage domain using OpenBIM		
Year: 2022	Data types:	Data management:	Data conversion:
Oostwegel et al. [95]	Spatial	Internal	Existing standard
Description: This work addresses the challenges of managing heritage buildings using Heritage Building Information Models (HBIM). It highlights the importance of high-quality data exchanges in the preservation and restoration of cultural heritage, utilising the IFC for standardising data. The study introduces a framework to develop Information Delivery Manuals (IDM) and Model View Definitions (MVD) specific to heritage, ensuring that geometric and semantic data are consistently and accurately shared across different software platforms, preventing data loss. A case study demonstrated this approach by enriching a historic building model with conservation data, further validating the interoperability of HBIM.			

Article 92	Title: Automated Schedule and Progress Updating of IFC-Based 4D BIMs		
Year: 2017	Data types:	Data management:	Data conversion:
Hamledari et al. [110]	Scheduling	Internal	Algorithm based
Description: This work explores methods to enhance construction project management by automating the update of schedules and progress information in 4D BIMs based on the IFC standard. The framework proposed integrates real-time progress data with the BIM model to track construction activities and automatically update the schedule, which reduces manual intervention and improves accuracy. A key contribution is the development of a structured process that links IFC data with a task-cantered network, allowing for seamless schedule updates and the early identification of delays, thus facilitating efficient construction management.			

Article 93	Title: Lumped record management method using BIM and dynamo for spalling maintenance		
Year: 2024	Data types:	Data management:	Data conversion:
Cho et al. [144]	Facility management	Internal	Algorithm based
Description: This work introduces a system to streamline the maintenance of concrete spalling by using BIM and Dynamo scripting. This method integrates spalling maintenance data from Excel into 3D BIM models, allowing for a visual and automated update of maintenance histories within the model. By automating this process, it enhances efficiency and reduces manual data input errors, offering a more accurate and intuitive way to manage spalling issues in both buildings and infrastructure			

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