BIM and Asset Management (AM) Interoperability: Current Status and Research Directions towards the adoption of Digital Twins

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what was known before:

- The absence of a critical overview of issues and research related to BIM-AM interoperability**.**
- The entire theoretical framework of BIM data being integrated with real-time data, from O&M databases, sensors, and internet of things (IoT) devices, is predicated on the assumption that data can be exchanged simultaneously between software programs.

what this paper contributes to:

- Reviewing and analysing the trends and overview of the BIM-AM interoperability publications**.**
- Analysing the articles yielded a categorisation of the interoperability contribution into four main areas: identification, integration, exchange and verifications.
- Categorizing the integrated digital delivery into four main outputs: digital model, digital mirror, digital shadow, and digital twin.
- Presenting the different layers required for effective DT interoperability.

Abstract

Digital Twin (DT) is seen as the new shift paradigm for digital transformation in the post-pandemic-built environment sector. Learning from the implementation of BIM for Asset Management (AM), there are recurring themes that the interoperability challenge is the critical barrier to firstly overcome. The absence of a critical overview of issues and research related to BIM-AM interoperability hinders the achievement of sustainable and effective integration between the two systems. Therefore, this paper aims to review and analyse the trends and overview of the BIM-AM interoperability publications, identify and classify the major research topics on BIM-AM interoperability and proposes future research interoperability directions for DT initiative adoption. Consequently, a systematic review of the work done to achieve interoperability in the operation stage, using a wide range of digital technologies was conducted. The review covers journal articles published between 2010 and 2020 related to the interoperability challenges between BIM and AM and real-time data sources. Our search query returned 576 articles, of which 64 met our inclusion criteria. Analysis of the articles yielded a categorisation of the interoperability contribution into four main areas: identification, integration, exchange, and verifications and also categorisation of the integrated digital delivery into four main outputs: digital model, digital mirror, digital shadow, and digital twin. The review, armed with the maturity stages of digital transformation proposed by ISO 19650 -2018, presented the different layers required for effective DT interoperability. The review also showed that more research is needed to characterise the best practice for data integration, develop cross-mapping ontologies for semantic alignment, and finally evaluate the business values of DT adoption.

Keywords: Interoperability, Digital Twin, Facilities Management, Assets Management, Building Information Modelling, BIM.

1. Introduction

While every industry is thinking about reshaping their business to thrive in the post-COVID-19 era, the architecture, engineering, construction, and operation (AECO) industry is emerging the Digital Twin (DT) initiative to build a new more intelligent, more productive, and safer built environment. This initiative is aligned with Industry 4.0 to advance new practices and tools to overcome the legacy associated with saying “BIM” for almost a decade. A DT refers to a digital replica of physical assets, processes, and systems (Lu et al., 2020a). This twin would enable the AECO sector to collaborate virtually, present sensor data, simulate conditions quickly, realise outputs of the what-if scenarios undoubtedly, predict results more accurately, and provide instructions to manage the physical world more effectively. Grieves and Vickers (2017) argued that DT's rationality definition is to have just the efficient data without intensively using resources, in other words, an integration between dynamic modelling with real-time optimisation through the whole lifecycle. Building information modelling (BIM), according to the ISO 19650 series, “*is about getting benefit through better specification and delivery of just the right amount of information concerning the design, construction, operation, and maintenance of buildings and infrastructure, using appropriate technologies”*. BIM is, to an extent, seen as an analogue to DT in the AECO sector. For this paper's argument, the authors identify BIM as an environment where processes, technologies, and resources are integrated for better delivery. In contrast, DT is an advanced deliverable of this integrated environment. In this analogy, both BIM nowadays deliveries for AM and DT have one main challenge hindering their adoption: data interoperability (Matarneh et al., 2019b). That challenge is the critical barrier to overcome, as the entire theoretical framework of any information management technology is predicated on the assumption that data can be exchanged simultaneously between software programs (Farghaly et al., 2018).

Data interoperability is the ability that all other parties can correctly interpret data generated by any one party. Also, it enhances the data exchange between two or more diverse systems to facilitate automation and avoidance of data re-entry (Shen et al., 2010). To achieve effective data exchange between applications, the proposed solution should achieve both semantic and syntactic interoperability (Farghaly et al., 2019). Syntactic interoperability solutions identify an agreed exchange format to transfer data, and semantic interoperability solutions identify a set of terms and data requirements to enable interoperation using the agreed exchange format defined by syntactic interoperability. Several works were conducted to achieve both semantic and syntactic interoperability between BIM and AM platforms, with more concentration on syntactic interoperability (Cavka et al., 2017). Despite all the efforts and contributions, the construction industry's available solutions for interoperability are still insufficient to leverage DT's potential (Sacks et al., 2020). A comprehensive review of previous research can provide significant benefits in identifying areas where additional research work is required, and in the process, discerning future directions for the development of the effective interoperability environment of the DT initiative.

Despite that, there are several reviews regarding implementing BIM for Facilities Management (FM) in general and AM in particular (Matarneh et al., 2019b, Gao and Pishdad-Bozorgi, 2019), we argue that the state-of-the-art of BIM-FM interoperability approaches has received limited attention. There are some reviews focused on BIM integration with a particular technology only for operation and maintenance stage such as the Internet of Things (IoT) (Tang et al., 2019) and other focused on digitalisation in general in FM (Wong et al., 2018). Even in Ozturk (2020), which concentrates only on the interoperability in BIM for AECO industry, has not unveiled detailed results about the BIM-FM interoperability approaches and just concentrated on a bibliometric search, and a scientometric mapping and analysis of interoperability in BIM research. Evidently, the literature lacks a concrete systematic review of the current semantic and syntactic interoperability approaches for BIM-FM integration, a limitation which was the crucial driver for conducting this research. In particular, we try to address this by answering the following:

1) What semantic and syntactic aspects must be addressed to achieve effective interoperability between BIM and AM?

2) What are the different approaches to achieve these aspects? Which are the limitations of these approaches?

3) How can these approaches utilise for effective DT adoption?

This research contributes as a fundamental early step in formulating how the digitalisation of the built environment assets can be considered, and how integration approaches can be identified and achieved to achieve the DT initiative's benefits. At the crux, this research is not providing a glistening answer for DT adoption in AECO industry, and it is a piece of enlightenment towards what should we learn from the previous work in the BIM area to demystify some of the main challenges and opportunities related to interoperability in the emerging DT initiative. It is worth noting that this review cannot be considered by any means as exhaustive since DT technology is continuously growing at a breakneck pace. The remainder of this work is organised as follows. Section 2 presents a brief overview of interoperability in the AECO sector and classification of integrated digital delivery based on their integration maturity. The method followed to conduct the systematic literature review is outlined in Section 3. The descriptive analysis of the retrieved literature is presented in Section 4, while in Section 5, content analysis is presented based on the different semantic and syntactic interoperability aspects identified. Relevant open issues, trends, and further research lines are discussed in Section 6 and represented based on the different digital transformation layers proposed by ISO 19650 (2018).

2. Research Background

2.1. BIM-FM Interoperability

Due to the diversity between the BIM platforms and the AM platforms, the interoperability between them is one of the main challenges in implementing BIM in AM practice. Massive efforts are being made to introduce open data standards, such as the industry foundation classes (IFC) and Extensible Markup Language (XML) schemas, and structured specifications such as the construction operations building information exchange (COBie) to solve the interoperability issue (Azhar et al., 2015). These open data standards can link easily and smoothly between the BIM data and the AM data. However, these mentioned approaches still have their inherent limitations. To achieve the integration between BIM and AM systems, the information required for AM has to be extracted from the Building information model and linked to a relevant database that stores all information related to the built asset in order to form an Asset Information Model (AIM) (Kivits and Furneaux, 2013). The AIM provides the underlying foundation for AM improvement. However, this process is filled with interoperability obstacles (Eadie et al., 2015).

Lee et al. (2013) observed that the technology's quality variable for BIM acceptance has to achieve both compatibility (syntactic interoperability) and output quality (semantic interoperability). Semantic interoperability is defined as "*the ability of information systems to exchange information based on shared, pre-established and negotiated meanings of terms and expressions*" (Veltman, 2001). In other words, the data is exchanged between two or more systems and shall be understood by each system. Semantic interoperability is required to achieve other types of interoperability, such as syntactic ones. Syntactic interoperability refers to the ability to prepare two or more systems for communicating and exchanging data using specified data formats and communication protocols (Kubicek et al., 2011). As the interface and programming languages are usually different systems, several obstacles need to be overcome to achieve the syntactic interoperability, such as a) identifying all the elements in the various systems; b) establishing rules for structuring these elements; c) mapping, bridging, creating cross-mapping between equivalent elements using schemas, etc. ; d) agreeing on equivalent rules to bridge different cataloguing and registry systems. Most of the available work on BIM-AM interoperability has concentrated on developing technology-driven functions and applications to overcome the syntactic interoperability barrier rather than developing computable information requirements for better semantic interoperability (Cavka et al., 2017). These efforts have provided different approaches to link quickly and smoothly between BIM and AM data through a standard data format. These approaches include the IFC, MVD and proprietary middleware (for example, Ecodomus) (Ibrahim et al., 2016).

Even with these approaches, syntactic interoperability solutions alone cannot ensure that BIM-AM integration could achieve the expected benefits and results. Abanda et al. (2015) argued that the optimum transformation between systems relies on the data format, which is supposed to be integrated with BIM. Pärn et al. (2017) critiqued that semantic interoperability is the single most crucial interoperability challenge to overcome when integrating BIM data with other systems such as AM platforms. Ozorhon and Karahan (2016) added that the required information and technology availability are essential factors in BIM implementation. A case study of an educational institution (Thabet et al., 2016) illustrated that the most common obstacle in BIM-AM integration is that asset data is scattered and unstructured. The components' data is not integrated or even referenced with other related data/information. Bercerik-Gerber et al. (2012) emphasised data heterogeneity by observing that more than 80% of the AM team's time is consumed finding relevant information that designers have often disregarded in earlier stages. Kim et al. (2018) argued that identifying only the required information will not achieve efficient semantic interoperability between BIM and asset management; they suggested that providing an object-oriented cross-domain linking with the required information can be a more efficient adequate solution. Pauwels et al., (2015) considered that the maximum benefit for the integration and addressing of IFC-based data through different BIM implementations could be tackled by utilising linked data technologies. Hu et al. (2018) also argued that an ontology is required to cross-link building performance with other building information, and Linked Data offers a mechanism to facilitate meaningful sharing of cross-domain building information. Several researchers argued that utilising semantic web technologies and linked data should tackle the interoperability issues across AECO (Törmä, 2014, Pauwels et al., 2018). Also, Sacks et al. (2020) stated the importance of developing and implementing solutions to enhance the semantic enrichment and graph representations of BIM models. Strategic planning is the key towards an effective implementation of BIM in the AM sector (Chunduri et al., 2013). In other words, a well-executed plan for exchanging data from BIM platforms to AM systems is crucial for achieving the required interoperability between the two systems. Both frameworks, proposed by Pishdad-Bozorgi et al. (2018) and by Farghaly et al. (2018), represents the process for successful BIM-AM integration (Figure 1). Based on the discussion as mentioned earlier, the solution towards interoperability requires to include four distinct aspects represented in the I-IEV framework: namely, identification, integration, exchange, and verification (Figure 2). In Figure 2, the different approaches, and methods to achieve these aspects are illustrated and they are discussed in Section 5.

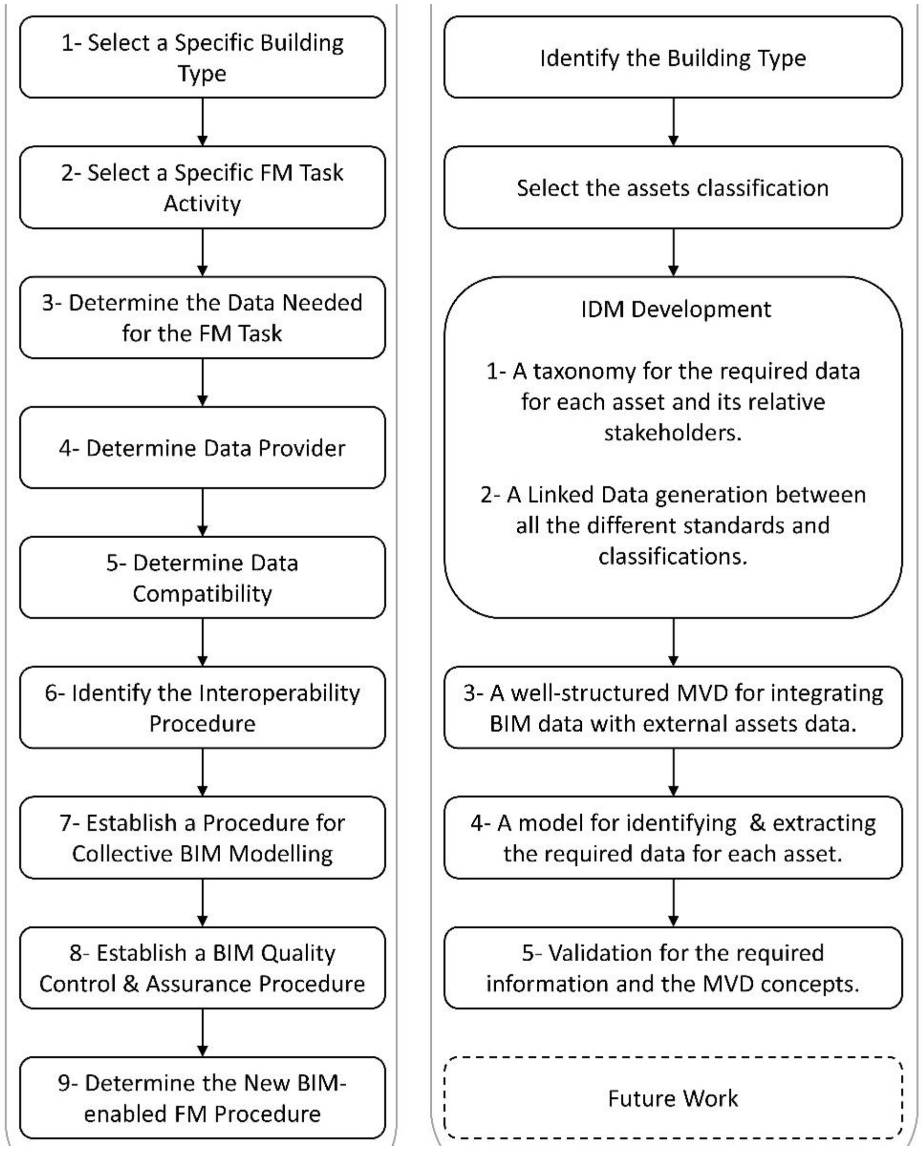

Figure 1: Two framework by Pishdad-Bozorgi et al. (2018) and by Farghaly et al. (2018) to effectively integrate data between BIM and AM systems.

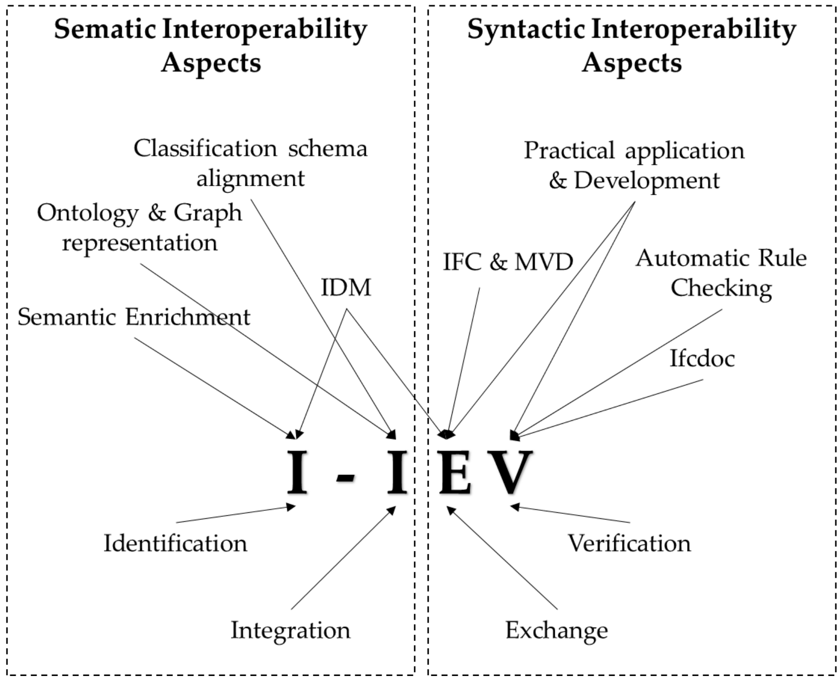

Figure 2: I-IEV framework representing the semantic and syntactic interoperability aspects.

2.2. Integrated Digital Delivery

There are diverse viewpoints on the relationships between Digital Twin and other concepts related to integrated digital delivery, and associated technologies such as simulation-based on BIM, Augmented Reality (AR) and Virtual Reality (VR), and smart systems based on Cyber-Physical Systems (CPS), IoT and BIG Data analytics (Lu et al., 2020d). Although these concepts are closely related, they, by their nature, are different on the concept, core elements, technologies adopted, level of data integration and applications. Digital Twin is based on developing a digital replica of a real-world asset in the built environment context. While this looks close to simulation attained by BIM, Digital Twin provides much more than BIM. The main difference between BIM and Digital Twin is that Digital Twin requires a high-fidelity representation of its physical asset's operational dynamics, which most of the Building information models lack. This operational information enables real-time synchronisation between the digital asset and physical asset (Schleich et al., 2017). Building information models focus on what could happen in the real world and what has happened, but not what is currently happening. Digital Twin can be utilised to monitor and control what is happening in real-time and predict what will happen based on the operational dynamics (Lu et al., 2020d). Therefore, the seamless integration of BIM data with AM data can function as the 'back-end' data for Digital Twin. An integrated digital asset of a physical asset helps understand how assets operate on a broader system and interact with other assets. The higher the level of data integration between the physical asset and digital counterpart, the better understanding of the physical world. Kritzinger et al. (2018) argued that some digital representations are modelled manually and are not automatically connected with any existing physical object, while, others are fully integrated with real-time data exchange. Therefore, they proposed classifying DT's maturity in manufacturing into three terms: Digital Model, Digital Shadow, and Digital Twin. To fit with the AECO context, the authors would like to propose one more term called 'Digital Mirror'. Figure 3 represents the proposed four integrated digital deliverables based on their data integration level, namely, Digital Model, Digital Mirror, Digital Shadow, and Digital Twin.

Digital Model is the first integrated deliverable from a maturity perspective where a digital representation of an existing or planned physical object is modelled (Kritzinger et al., 2018). In that level, no automated data exchange between the physical object and the digital object occurs. These models are utilised for 3D coordination, bill of quantities extraction, simulation of construction sequences, structural analysis, energy simulation and any other application which does not use any form of automatic integration (generative and computational design). Digital data of existing physical objects such as laser scanning point clouds and capital expenditure (CAPEX) asset information can still be used to develop these models, but all the data exchange is done manually. In the digital mirror deliverable, the digital asset data and physical asset data are mapped through semantic alignment (Sacks et al., 2020) and/or product data templates (Farghaly et al., 2018). This cross-mapping provides an opportunity to automatically exchange data from the digital asset to a physical asset's operating platforms using MVDs. However, a change in the physical asset does not automatically change or even notify in the digital asset, which can then be represented as synchronisation only. On the other hand, in the digital shadow deliverable, automatic flow exists between the physical asset and digital asset. Consequently, any change in the physical asset is captured and visualised in the digital asset. Nevertheless, a change in the digital asset state has no direct effect on the physical asset. Example of the digital shadow is representing the real-time data from sensors and IoT devices (Dynamic datasets) associated with the Building information models (Static datasets) (Lu et al., 2020a). In other words, the physical asset is fully synchronised with the digital asset with the assistance of building management systems (BMS) applications using Dynamic datasets. Finally, digital twin level is where there is a two-way link between the digital and physical world. In this level, the digital asset platform does not only capture and store changes of the physical asset but also can tweak the physical asset's operation based on supervised machine learning and artificial intelligence.

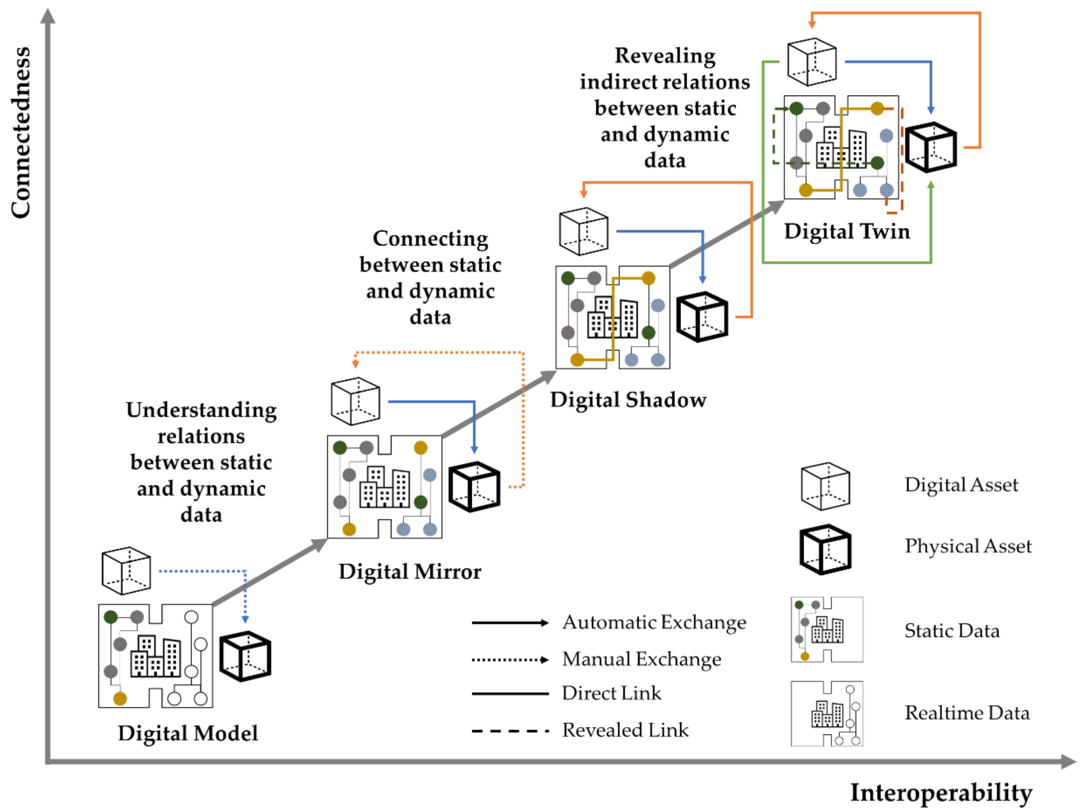

Figure 3: Integrated digital deliverables based on the level of data integration.

3. Methodology

This section presents the methodology utilised in the paper to select the most appropriate recent developments as published in the literature, covering the topics of BIM-AM Interoperability and Digital Twin in the AECO industry. In this study, a systematic literature review was conducted to offer a comparatively scientific, holistic, unbiased, and logical approach to investigate studies that can answer the three research questions, ensuring this research's quality of evidence. To provide a transparent, reproducible and scientific literature review of BIM-AM Interoperability approaches, the process suggested by Briner and Denyer (Briner and Denyer, 2012) as well as some recommendations for conducting the systematic review (Harari et al., 2020) and some features of the PRISMA statement (Moher et al., 2009) have been adopted. The overall methodological approach includes the three following steps: 1) Study locating and identification, 2) Study selection and evaluation, and 3) Study analysis and reporting.

3.1. Study locating and identification

Two digital databases were explored to search for target articles. Web of Science (WoS) is a database that offers cross-disciplinary research in sciences, electronic technologies, social sciences, arts, and humanities. The second database is ScienceDirect which is an extensive database of scientific techniques and medical research. These two databases sufficiently cover BIM and DT technologies and their applications in AECO sector and provide a broad view of existing research in a comprehensive but relevant range of disciplines. The selection of the different databases ensured the systematic inclusion of useful and relevant publications in the study field, safeguarding that no vital information would be missed (Harari et al., 2020). To retrieve the literature on BIM-AM Interoperability, a set of search commands were applied to verify a paper's title, abstract and keywords. The 'keywords' approach is widely adopted for systematic data selection. 'BIM' or 'building information modelling' or 'building information management', 'digital technology' or 'digital asset', 'Digital Twin or 'DT' as well as other terms related to AM, including 'facilities management' or 'refurbish*' or 'asset management' or 'space management' or 'maintenance' and as well as terms related to interoperability, including 'integration' or 'exchange', were the search commands. All the search commands are limited to journal articles only because they usually provide more comprehensive and higher-quality information than other types of publications, and most reviews in the area of construction management have only covered journal articles. Therefore, conference papers were excluded from the search. In addition, the search commands were limited to English language and time-span from 2010 till 2020. The systematic literature search was carried out during January 2020, and the results were subsequently updated during June 2020. After removing the duplications of journal articles extracted from the two different databases, 576 articles were identified (Figure 4).

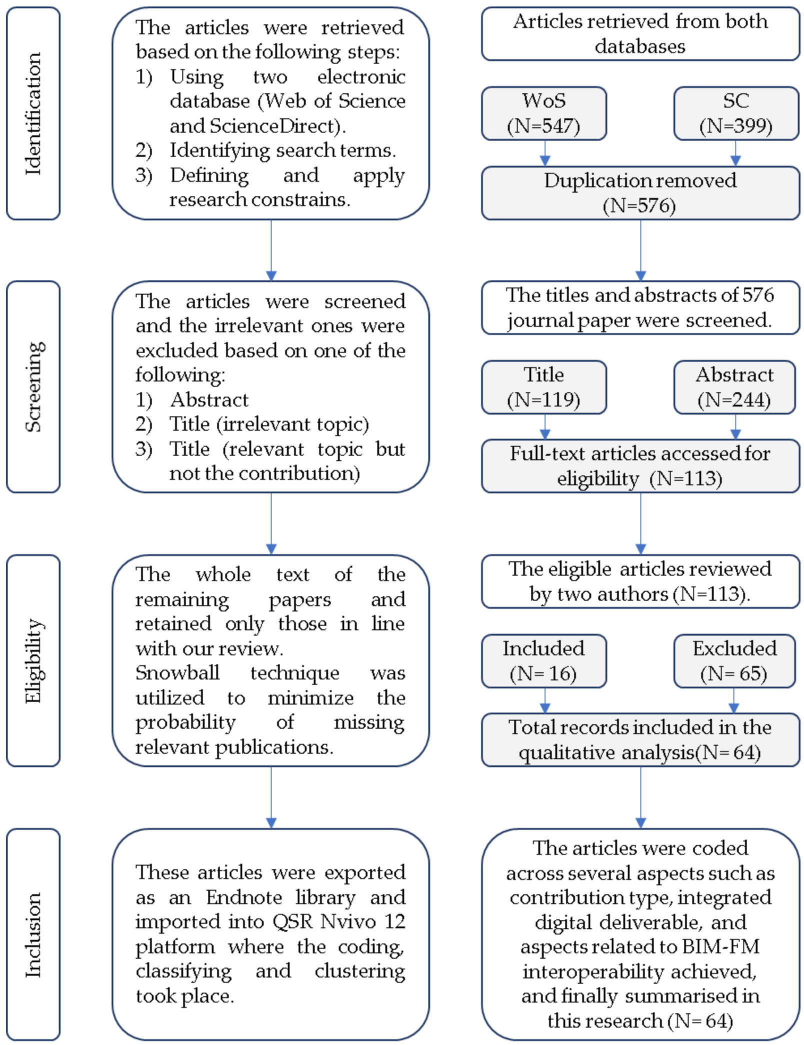

Figure 4: Flow chart of the research strategy.

3.2. Study selection and evaluation

The eligibility of the retrieved literature was evaluated independently by the authors based on a set of predefined inclusion and exclusion criteria. First, several papers were excluded based on the title and/or the content of their abstract. Next, we considered the remaining papers' whole text and retained only those in line with our review. Snowball technique was then utilised to minimise the probability of missing relevant publications. Snowballing refers to utilising the references of an included article for review to identify other relevant articles to be added for the systematic review (Booth et al., 2016). The same criteria utilised for the selection were adopted for snowballing, which led to additional articles. The final unique set of publications remaining (64 journal papers) were analysed in depth.

3.3. Study analysis and reporting

The 64 articles related to research questions were then downloaded and attached to the references in Endnote (Reference manager platform). These articles were exported as an Endnote library and imported into QSR Nvivo 12 platform where the coding, classifying and clustering took place. NVivo enables coding for different articles to be represented visually, with networks and connections between articles to be identified (O'Neill et al., 2018). The articles were coded across several aspects such as the FM application, contribution type of the article, integrated digital deliverable, and aspects related to BIM-AM interoperability achieved in the reviewed article. Figure 5 presents an example of the codes assigned to the reviewed articles.

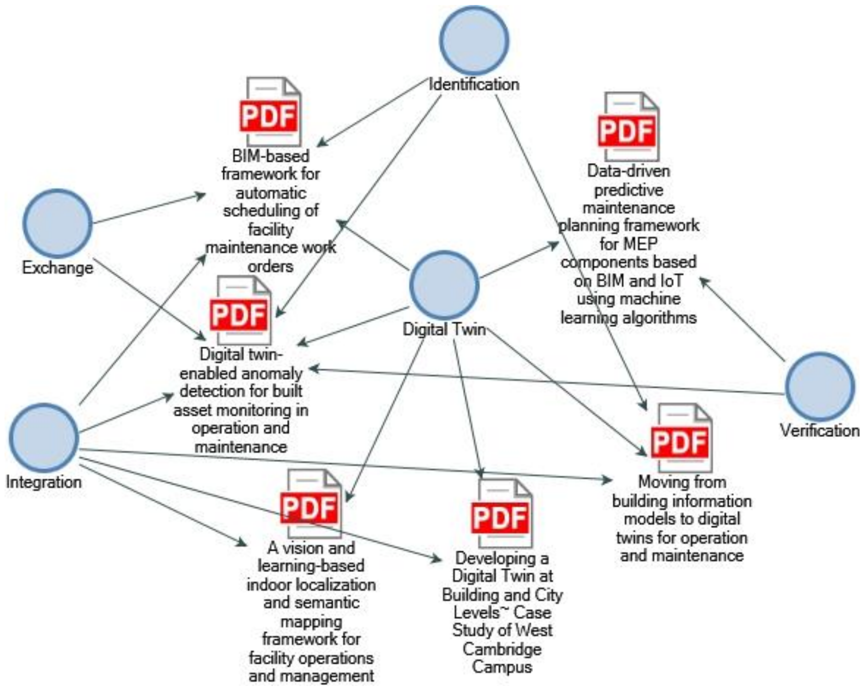

Figure 5: Nvivo Screenshot representing an example of coding

4. Descriptive analysis results

The aim behind conducting a descriptive analysis is threefold: 1) it provides interesting insights for the current research trends and their importance regarding the interoperability in the AECO sector. 2) it helps visualise the multidisciplinary approaches developed so far in the area of BIM-AM interoperability, and 3) it supports the classification structure proposed in Section 5. The descriptive analysis in this research is based on the following two critical criteria.

4.1. Distribution by Years and Journals

The chronological distribution of journal articles addressing the interoperability between BIM and AM is represented in Figure 6. Overall, the results show that the topic had an increasing interest to researchers since 2017, with many publications reaching a pack of 17 articles in 2019. The possible explanation for such a trend could be the growing adoption of advanced digital technologies in the AECO industry and the government requirements for advanced digital transformation based on their new standards and guidelines such as ISO 19650 (2018). As the expression ‘DT’ is relatively new in the AECO sector, most of the research conducted concentrates on integrating BIM data with AM data through the available exchange specifications such as IFC and COBie. Figure 6 is colour-coded to represent the integrated digital deliverable of the reviewed articles concerning the categorisation of the integrated digital delivery into four main outputs: digital model, digital mirror, digital shadow, and digital twin. The following is a list of some (not all) of the top journals included in this literature search: Automation in Construction (21 articles), Advanced Engineering Informatics (6 articles), Facilities (5 articles), Engineering, Construction and Architectural Management (4 articles), Journal of Facilities Management (3 articles), Journal of Information Technology in Construction (3 articles), and Journal of Building Engineering (3 articles). Other journals contain relatively less coverage of the topic with no more than two relevant articles.

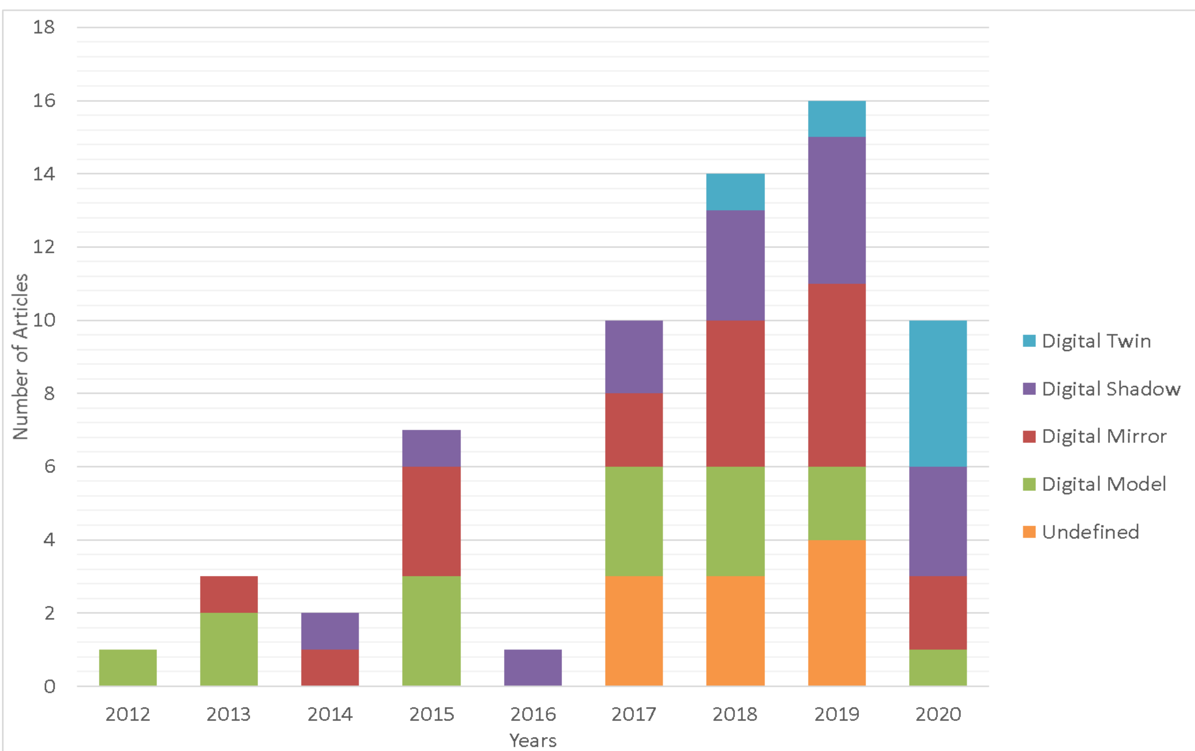

Figure 6: Distribution of reviewed papers by publication date and type of digital deliverables.

4.2. Distribution by Outputs

This paper aims to provide a categorical literature overview among the different aspects of BIM-AM interoperability and the direction for utilising these aspects for successful DT implementation in the AECO sector. Therefore, the categorisation of BIM-AM interoperability aspects and integrated digital delivery, mentioned in section 2, were utilised. The majority (33%) of the reviewed literature is categorised with the integrated digital deliverable as 'Digital Mirror'. Meanwhile, there are similar concentrations of 28% within the interoperability aspect of the three aspects: 'Identification', "Integration" and 'Exchange' and less concentration on "Verification". A combined analysis of the interoperability aspect and maturity of the integrated digital deliverable provides more insights (Table 1). It is important to note that the total number of articles below the interoperability aspects is higher than the actual number of reviewed articles as some articles contribute in more than one aspect and therefore are counted more than one time in the table. For example, Farghaly et al. (2020) cover both the exchange and verification aspects by developing an MVD and validating the IFC model against a set of rules using Ifcdoc. The table represents the majority of the work is in the digital mirror level, expected, and specifically on the integration and exchange aspects. This lead to the development of several MVDs and software plug-ins (Farias et al., 2018, Pinheiro et al., 2018a, Heaton et al., 2019). The table also shows that ignoring the undefined ones where no exact digital deliverable classification was possible, the relative number of identification aspect decreases with an increase in the verification aspect. As the DT in the AECO sector still in its infancy, there is one article till June 2020 concerning Digital Twin, which includes prediction using machine learning (Cheng et al., 2020). The other five articles categorised as digital twin included work which can facilitate the transition from digital shadow to the digital twin. However, they have not included the automatic two-way link between the digital and physical worlds (Wei and Akinci, 2019b).

Table 1: Digital maturity level and I-IEV contribution classification matrix

Contribution Aspect / Digital Maturity	Identification	Integration	Exchange	Verification
Digital Model – 15 papers	5	4	6	5
Digital Mirror – 18 papers	5	9	10	7
Digital Shadow – 15 papers	7	7	10	6
Digital Mirror – 6 papers	3	5	2	2
Undefined – 10 Papers	9	4	2	1

5. Content Analysis

Strategic planning is the key to effective BIM implementation in the AM sector (Chunduri et al., 2013). In other words, a well-executed plan for exchanging data from BIM platforms to AM systems is crucial for achieving the required interoperability between the two systems. Therefore, the literature review is categorised and presented as an interoperability plan for exchanging the data from the BIM tools to the AM systems. The 64 reviewed journal articles in this research are illustrated in Table 2 and how the four I-IEV contribution categories are covered in each article.

Table 2: Reviewed articles and their contribution.

Authors	Year	Identification	Integration	Exchange	Verification
(Alnaggar and Pitt)	2019	No	No	Yes	No

(Alnaggar and Pitt)	2019	Yes	No	No	Yes
(Alwan and Gledson Barry)	2015	Yes	No	No	No
(Andriamamonjy et al.)	2018	No	No	Yes	Yes
(Arayici et al.)	2018	No	No	Yes	No
(Burak Cavka et al.)	2018	No	No	Yes	No
(Carreira et al.)	2018	No	Yes	Yes	Yes
(Cavka et al.)	2017	Yes	No	No	No
(Chen et al.)	2018	Yes	Yes	Yes	No
(Chen et al.)	2020	Yes	No	Yes	Yes
(Cheng et al.)	2020	No	No	No	Yes
(Curry et al.)	2013	No	Yes	No	No
(Dias and Ergan)	2020	Yes	No	No	No
(Ding et al.)	2020	Yes	No	No	No
(Dixit Manish et al.)	2019	No	No	Yes	No
(East et al.)	2013	Yes	No	No	No
(Edirisinghe et al.)	2017	Yes	Yes	Yes	No
(El Asmi et al.)	2015	No	No	Yes	No
(Farghaly et al.)	2019	No	Yes	No	No
(Farghaly et al.)	2020	No	No	Yes	Yes
(Farghaly et al.)	2018	Yes	No	Yes	No
(Gao and Pishdad-Bozorgi)	2019	Yes	Yes	Yes	No
(Gouda Mohamed et al.)	2020	No	Yes	No	No

(Heaton et al.)	2019	Yes	No	Yes	No
(Hosseini et al.)	2018	Yes	No	No	No
(Hsieh et al.)	2019	Yes	No	No	No
(Ilter and Ergen)	2015	No	Yes	Yes	No
(Jeong et al.)	2014	No	No	Yes	No
(Kang and Choi)	2015	Yes	No	No	No
(Kasprzak and Dubler)	2012	No	Yes	Yes	No
(Kassem et al.)	2015	No	No	No	Yes
(Kim et al.)	2018	No	Yes	No	No
(Liu and Gao)	2017	Yes	No	No	No
(Lu et al.)	2020	No	Yes	No	No
(Lu et al.)	2020	Yes	Yes	No	No
(Lu et al.)	2020	Yes	Yes	Yes	Yes
(Matarneh Sandra et al.)	2019	No	No	Yes	No
(Matarneh et al.)	2019	Yes	Yes	Yes	No
(McArthur et al.)	2018	No	No	No	Yes
(Miettinen et al.)	2018	Yes	Yes	No	No
(Motamedi et al.)	2014	Yes	Yes	No	Yes
(Motamedi et al.)	2016	No	Yes	Yes	Yes
(Motawa and Almarshad)	2013	No	No	No	Yes
(Niknam and Karshenas)	2017	No	Yes	No	No
(Pärn et al.)	2017	Yes	Yes	No	No

(Pärn and Edwards)	2017	No	No	No	Yes
(Patacas et al.)	2015	Yes	Yes	Yes	No
(Pinheiro et al.)	2018	No	No	Yes	Yes
(Pishdad-Bozorgi et al.)	2018	No	Yes	No	Yes
(Rodriguez-Trejo et al.)	2017	Yes	No	No	No
(Sadeghi et al.)	2019	No	No	Yes	No
(Shalabi and Turkan)	2017	Yes	No	Yes	Yes
(Tan et al.)	2018	Yes	Yes	No	No
(Tang et al.)	2020	No	No	Yes	No
(Thabet and Lucas)	2017	No	Yes	Yes	No
(Thabet and Lucas)	2017	No	Yes	No	Yes
(Venugopal et al.)	2015	No	Yes	Yes	No
(Wanigarathna et al.)	2019	No	Yes	Yes	No
(Wei and Akinci)	2019	No	Yes	No	No
(Wijekoon et al.)	2018	Yes	No	No	No
(Wong et al.)	2018	Yes	Yes	Yes	Yes
(Yalcinkaya and Singh)	2019	No	No	No	Yes
(Yalcinkaya and Singh)	2019	No	No	Yes	Yes
(Zhu et al.)	2019	Yes	Yes	No	Yes

5.1. BIM-FM Information Identification

Identifying the required information from the building information models for AM is a necessary and critical step for implementing BIM in AM. The absence of this information would have a negative impact on building performance, as it would be the reason for workflow variabilities (Arashpour and Arashpour, 2015). Variability can be reduced by defining the owner’s requirements, illustrating the appropriate workflows, and assigning the new jobs related to the BIM data in an early stage of the project. The required information should be presented in a taxonomical structure, as developing a taxonomy of the objects of a knowledge field can provide a common terminology that eases the sharing of knowledge and supports decision-making (Becerik-Gerber et al., 2012). The known concept can solve the problem of data consistency; extract, transform, and load (ETL) which has been a robust paradigm through starting the trajectory of BIM perspective definition (BPD) metadata structure (Kang and Choi, 2015). This metadata endorses user perspectives' variability to distil only the needed information from the heterogeneous data source and determines a prototype conversion logic that explains how to transform the extracted data (Heaton et al., 2019). However, the information required from the building information models varies depending on the facility team’s mission and goals, and the assets and building characteristics. Consequently, the required information cannot be generalised for all FM activities or all assets or even by the asset system.

Predominantly, the required information and its incomprehensible content in the FM industry encourages many researchers to investigate the required information, its uses, and required level of detail. For instance, early researches (Hunt, 2011, Becerik-Gerber et al., 2012, Wang et al., 2013) proposed different high-level hierarchical classification and others proposed a classification based on standards or defined templates such as asset register (Patacas et al., 2015) and COBie (Kassem et al., 2015, Pishdad-Bozorgi et al., 2018). Cavka et al. (2017) and Thabet and Lucas (2017b) argued that computable requirements could be only effectively identified by breaking down the owner requirements, demonstrating the necessity to know how to grapple with the superfluous, tedious information. Meanwhile, it is imperative to know how to reach required information to operate and maintain equipment and systems in buildings efficiently and effectively, and ensuring they are consistent with the required handover information (Cavka et al., 2015). However, Alnaggar and Pitt (2019a) concluded that reaching this level of a seamless attribute is pivotal for O&M personnel, which will have many advantages such as: optimising O&M activities, enhancing energy efficiency, and minimising person-hour and equipment/system crashes. They considered that these numbers of sets of information are the central core of establishing the COBie management procedure during all building lifecycles, which thrives the excellent preparation and early engagement from client FM at the strategic phase of the adequate project AIR. Therefore it is essential that the design and construction teams shall review the information requirement documents, and provide a response or request clarification about the COBie document so any possible problems can be then revealed like ambiguities naming conventions, classification standards or absence of zoning strategy (Alnaggar and Pitt, 2019a). Martarneh (2019a) suggested a conceptual framework that merges seamless BIM information and FM system utilising an open-data format to surmount interoperability issues and then store the combined data in an external database establish the generation of COBie spreadsheets. They also tried to overcome the absence of data related to manufacturers, such as spares, warranties details, installing date, expected life, which implies that as-built Building information models do not contain the manufacturers' product information. It has extra effort to collect the information manually by FM teams from different stakeholders. (Motamedi et al., 2014) proposed a framework for producing knowledge-assisted BIM-based, utilised in an FM Visual Analytics System (FMVAS). Therefore, they illustrated that by classifying a unique ID for each object in the design phase to benefit from enriching the O&M software databases. They also identified the different data such as assets/location definitions to link that to different data in various applications related to O&M software systems. (Chen et al., 2020) demonstrated the importance of visualising unshown information for a significant amount of equipment which can support the tremendous amount of required information for decision-makers in FM. However, to overcome the deficiency of COBie as an information processing format on which it does not provide details on the required data for FSE inspection and maintenance, when it has to be provided and who is the concerned person to provide it?. They also examined application models of inspection information, and consequently, they developed an accurate COBie spreadsheet including the required information such as spatial data, FSE information and related documents.

Despite all the different classifications and long lists of diverse required information were formed, it has been argued that identifying only the required information will not achieve efficient semantic interoperability between BIM and asset management (Kim et al., 2018). Apart from information needs, several other essential factors need to be considered in offering a knowledge resource for asset management, such as available, reliable and valid knowledge sources are required, and relations between the different data sources need to be considered. Therefore, providing object-oriented cross-domain linking with the required information can be a more efficient and adequate solution. Predominantly, the absence of rich and dense interoperability between BIM and FM software has been considered as one of the main obstacles for implementing BIM in FM, on the other hand, the data needed for FM is monotonous and fragmented, and demands to be tackled to match the bespoke requirements of each stakeholder, expanding the complexity gap in data coherence among BIM and FM. (Patacas et al., 2015), showed that there are powerful motivations for expanding the BIM adoption with more rational approaches in FM applications. However, there are still some obstacles such as the polemic utilisation of open standards (IFC, COBie and another tested backing) to identify the information required for FM which demonstrate some deteriorates in providing some of the information aspects and factors needed for FM applications.

5.2. BIM-FM Information Integration

The IFC format has been utilised as the format for providing information exchange between BIM and AM; however, it still presents many challenges. Although the IFC schema is a rich and vast data model containing the required data for different applications and needs in the AECO domain, facilities managers do not usually use it. That is because IFC models either do not contain the required information or contain superfluous information, making it difficult to extract the required information. Therefore, the AECO sector has been moving in the direction of knowledge processing. In other words, there are directions to integrate BIM and FM data through model server technologies, single integrated/distributed federated databases and software-as-a-service using ontology approach. Ontologies excel at integrating data and resources from different knowledge domains and perspectives such as sensors, asset databases and building information models. Ontology reasoning capabilities also offer new creative ways to interpret data, information, and knowledge, and allow a more realistic representation of human behaviour and design knowledge than conventional tools. However, the practical application of ontology-based systems requires extensive knowledge of the domains involved and their correct definitions, and an IFC can express ontologies but is not in itself a well-defined ontology process for the development and publishing of ontologies and Linked Data. For establishing the ontology, an OmniClass classification's taxonomy has been implemented by (Lee et al., 2016a) to construct the classes and properties in which they suggested a framework for sharing construction defect data via the applicability of BIM and Linked Data.

According to El Asmi et al. (2015), Web Ontology Language (OWL) is the official ontology language established for the semantic web, which can be utilised for various application domains. It is a procedure for connecting information to manage, express, and reach by automated tools, the utilisation of semantic web extension is widely considered a solution regardless of its disadvantages. The main elements of the semantic web are, RDF (Resource Description Framework), OWL is the Web Ontology Language, a standard to write semantics, - SPARQL and Linked Data. IFC is essential in evolving construction projects, but it sometimes needs to gather additional information from external sources, that is why many researchers call for the alteration of the IFC model into an ontology language and, to add the rest of required information with additional, external, data to improve IFC semantically (El Asmi et al., 2015). Currey et al. (2013) demonstrated the utilisation of RDF and linked data for merging different cross-domain building data for cloud-based services which can be used to improve interoperability in terms of taking away data across repositories to reuse and share within feasible methods. Motamedi et al. (2014) proposed integrating computerised maintenance management systems (CMMS) with BIM to sort inspection and maintenance information. However, to tackle the necessity of this integration, it is essential to properly obtain the knowledge using techniques such as fault trees using a prospective of knowledge-assisted BIM-based VA. Another research has been carried out by Chen et al. (2018a) in which through three steps, an IFC schema extension is suggested. 1- to recognise what facility data is necessary to perform maintenance, 2- IFC extensions are planned to bridge information from Building information models to CMMSs / facility management systems (FMSs), 3-data mapping and data integration between CMMSs/FMSs and the Building information models are recognised based on the IFC extensions, simultaneously, this could be the potential to allocate Building information models to include facility maintenance data to obtain as-built Building information models (LOD 500) through these steps. Motamedi et al. (2016) illustrated the utilisation of Radio Frequency Identification (RFID) and BIM for FM in which, ontology similarity can be utilised to integrate building elements with BIM. They developed a technological technique to obtain lifecycle data by RFID tags and integrate analogues and entity sets into the IFC standard. “Begin with the End in Mind” (Covey, 1989), in other words, Wei and Akinci (2019a) proposed framework which can help FM by capturing facility entities and integrate them with their digital twin in a storage database. Instantaneously when associated to traditional techniques, the upgraded image-based indoor localisation and semantic mapping framework have many benefits such as it needs only picture as an entry to assist semantic knowledge, localisation techniques which overcome the current problem with localisation methods and eliminate any additional infrastructure such as the deployment of RFID tags.

On the other hand, Niknam and Karshenas (2017) identified some aspects to enhance ontology development in a multi-domain environment such as develop a single ontology that concerned all knowledge domains participating in the building lifecycle. However, each domain's development shall be independently by its ontology which must be associated with information exchange and by spreading a shared foundation ontology. Pärn and Edwards (2017) believed that it is remarkable that the paucity of protocols to report the integration of information and data between FM and BIM when they started to improve an API plug-in (FinDD) to computerise this procedure. However, they disclosed that although FinDD was established as a modified extension of COBie to meet clients requirements, further advancement is needed to moderate software uncompromising and enhance automation of semantic data integration, storage and analysis. Kim et al. (2018) proposed a process to connect the IFC entities with the FM work information. They improved a semantic relation between the classes of IFC, COBie and old maintenance work models. However, to provide a BIM methodology without precise BIM commercial applications, they claimed that the suggested technique could offer semantically link to BIM objects to the O&M records in the Semantic Web during this stage. Predominantly, data management's ontology can decrease superfluous data input, eliminate data and data problems through the allocation of understanding and reuse of data. On the other hand, Chen at al. (2018a) argued that Revit as a platform for 3D representation and medium for integrating the associated information to the O&M with a BIM-based automatic maintenance work order scheduling to plan FM work orders through support from IFC. Lu et al. (2020b) provided a DT-enabled anomaly detection method for asset capturing and its data integration technique based on IFC in day to day routine O&M management which accelerates decision making and potential for computerising the anomaly detection procedure. Their work considered a well-structured system to connect all assets efficiently, as well as the ability to handle required information. An ontology system produced from a semantic web technology module implementation depends on incorporating BIM-based tool data and semantic web technology (Gouda Mohamed et al., 2020). Concurrently, this can consider as an improvement to existing facilities' entities, develop the formalisation of existing data, enhance the usability and organise O&M applications during all facility lifecycle stages. However, one possible implication of this is that an integrated method for existing facilities semantic development from indoor digital scanning depiction phase to semantics portrayal and organisation phase is still not sufficiently addressed for rehabilitation functions.

5.3. BIM-FM Information Exchange

Research and prototype systems have already been developed to improve the syntactic interoperability between BIM and AM systems (Kang and Hong, 2015). Different approaches were developed and suggested using one of five methods or combinations of some or all of these methods suggested by Ibrahim et al. (2016). The four main approaches are manual or iterative spreadsheet-based, Industry Foundation Classes (IFC), Construction Operation Building Information Exchange (COBie) and Proprietary Middleware. Table 3: BIM-AM linking approaches and the corresponding methods to achieve the approach

Table 4: Approaches for data exchange between BIM and AM platforms.

Approach	Methods
Manual and Spreadsheets:	Extract, Transform & Load (ETL) and Data Warehouse (DW).
Industry Foundation Classes:	BIM-based neutral file format.
Construction Operation Building Information Exchange (COBie):	BIM-based neutral file format. Design Pattern and application programming interface (API). Extract, Transform & Load (ETL) and Data Warehouse (DW).
Proprietary Middleware:	BIM-based neutral file format. Design Pattern and application programming interface (API). Web service. Extract, Transform & Load (ETL) and Data Warehouse (DW). Information Delivery Manual (IDM) and Model View Definition (MVD).

It is commonly known that FM industry users still prefer to enter data manually using spreadsheets. That is deteriorated trajectory, which promotes the necessity of exploring and rethinking the fundamental value of BIM-FM integration obtained from enhancements of current manual and spreadsheets methods of information handover. With the manual spreadsheet-based approach, inputting, verifying, and updating the information in the FM systems is a costly and time-consuming process and there is no objective validation of the quality or the strength of the data entered. The principal advantage of this contextual ‘mend and make do’ approach is that the facilities team can operate it without making changes or revisions to their existing work processes, such as they may be. All of these parameters drove to the advancement of the standard IT options offered by the other three approaches of BIM (Becerik-Gerber et al., 2012).

The IFC-based approach is an open, vendor-neutral BIM data repository, specified and developed by BuildingSMART. IFC considered the only format for BIM data exchange relies on an unbiased file format that endorses a heterogenous BIM data structure without supporting the utilisation of data from the perspective of concerned stakeholders. As the IFC schema has a rich and vast data model containing the required data for different applications, construction professionals and software developers have worked on developing processes for the IFC sub-schemas (MVD) for each discipline improve the implementation of IFC. This process, as named by BuildingSMART as “An integrated process for delivering IFC based data exchange”, begins with capturing the user information requirements for exchanges using the IDM procedure, then transitioned into the IFC schema through the MVD technique. However, this process arises with the incomprehensible relation between IDM and MVD regarding appointing the users' responsibility for creating exchange requirement models. However, to overcome this inherent problem, Farghaly et al. (2020) improved the data exchange of assets that consume energy from BIM systems to the AM systems by adopting a participatory action research (PAR) approach for developing the IDM for the proposed MVD. This shows us the importance of involving the industry experts with focus groups to develop IDM model view concepts and map it to IFC schema for data exchange between two software platforms. Additionally, they created a Revit plug-in to manipulate the required assets’ data and relevant entities for the exchange. Pinheiro et al. (2018b) developed the Annex 60 MVD for data exchange from BIM platforms and Building Energy Performance Simulation (BEPS) tools. The developed MVD aims to overcome adding data into energy simulation models by providing IFC files with the required BIM data for energy simulation.

Similarly, Andriamamonjy et al. (2018) developed an MVD for data exchange to Modelica (BEPS tool). They also developed a Python-based tool (Ifc2Modelica) capable of translating the geometry, system and control information contained in IFC into a Modelica-based BEPS. Another route to improve the adoption of IDM and MVD approach, Tang et al. (2020) established a pivotal key for simplifying information exchange for "BIM assisted Building Automation System (BAS) design and operation using one of the BAS open communication protocol named Building Automation and Control Networks (BACnet) and open BIM standard Industry Foundation Class (IFC)". They utilised Revit as a 3D Building information model platform and a web browser to illustrate the application of the BACnet MVD for BAS information exchange. However, the BAS model has been included with BIM information in some FM platforms such as Archibus and EcoDomus, but these tools do not link to sensor control systems using BACnet protocol. Other research concentrated on the extension of IFC to integrate with other operating and maintenance datasets such as RFID (Motamedi et al., 2016), maintenance work orders (Chen et al., 2018b), asset performance monitoring (Lu et al., 2020b) and fire safety equipment (FSE) inspection and maintenance (Chen et al., 2020).

COBie used from FM standpoint, is a neutral file format defined by the MVD of IFC (Kang and Choi, 2015). The COBie approach is to enter the structured data as it is created during design, construction and commissioning (East and Carrasquillo-Mangual, 2013), facilitating the process of transferring information from BIM platforms to CAFM platforms. There are three formats for COBie-based information which can be provided and traded namely, IFC (STEP) standard, ifcXM and spreadsheet (Yalcinkaya and Singh, 2019b). The first two can be used associated with related users despite the necessity of some high tech skills which can be missing for some users. Spreadsheet format is the widely used format due to its familiarity and the high knowledge of end-users, then it is the vast and most suitable way to form and share COBie data. However, the urge to entirely automate the integration process of COBie data with Computer-aided facility management (CAFM) software applications have remained largely overlooked, indicating a critical gap in achieving semantic alignment (Alnaggar and Pitt, 2019a). The middleware considered as third party software to integrate data from BIM and exchange into AIM, this can be one-way integration or bi-directional integration which relies on the capacities of the platform, the idea of the integration is the model and data are sorted by the middleware and then transferred to FM system after checking and also it allows the possibility to modify with the user interface, there are some benefits such as it is a substitute to integrate the BIM data into current systems without the necessity to handover heterogeneous current information to a new system, however, it is an additional cost to the owner budget, and maybe additional skills shall be considered (Thabet and Lucas, 2017b).

The workflow of these different approaches often includes a COBie format spreadsheet as the exchange format for the BIM data to the AM systems (Ibrahim et al., 2016). That is because most of the CMMS systems such as the AiM system accept the COBie format spreadsheet as the primary format. The Manual or semi-automatic Spreadsheets approach can be utilised by extracting the required information for AM from the Building information model using BIMLink or Dynamo to a spreadsheet. The information in the spreadsheet is manually mapped onto a COBie format spreadsheet. In the IFC approach, practitioners utilise Solibri, one of the leading BIM platforms for quality control purposes, to verify and validate the COBie information within the IFC model and then export it in a COBie spreadsheet format. Also, the COBie extensions for Revit released by Autodesk and Ecodomus both automatically generate the required data in a COBie format. Although the entire information-capturing process from the Building information models, by any of the available approaches, seems to go smoothly, unexpected errors usually occur when importing the COBie spreadsheet into the AM systems (Pishdad-Bozorgi et al., 2018). Most of the errors are related to semantic interoperability, such as models containing superfluous information, missing information, absence of mapping predefined parameters and incompatible value types. Therefore, researchers should concentrate on scoping the computable information requirements for better semantic interoperability rather than concentrating on developing technology-driven functions and applications to overcome the syntactic interoperability barrier. Also, the outputs from the exchange process should be evaluated against several semantic rules for verification.

5.4. BIM-FM Information Verification

The verification of the interoperability solution is decomposed of two stages; namely, implementation and validation. After the requirements and process maps are defined in the form of a semantic interoperability solution such as IDM and the implementable machine-readable solution is developed such as an MVD, it is time to implement the whole solution in the software environment and apply it in different projects. (Jeong et al., 2014) revealed the implementation of an intermediate class package which automatically transform the BIM data into Modelica BEM (Revit2Modelica). This system is on the MVD for thermal simulation to easily enable the utilisation of BIM data in building energy simulation. However, the solution focuses only on energy simulation and can also be expanded to include more simulation fields such as daylight and photovoltaic. Shalabi and Turkan (2017) developed an application programming interface (API) based on open source IFC4 which grants users to import any data from the BEMS and CMMS in

XLS format. The implementation process is responsible for generating attribute for any missing one and label it with its value to the object's IFC-PROPERTY-SET, also search and replace if needed for any designated attributes in IFC-BIM. Yalcinkaya and Singh (2019b) captured the architecture implementation of VisualCOBie in which divulge the intricacy and multiplicity of the user and technical backgrounds such as the vigour of the application for big data and user traffic and supposed to be an improvement to the functionality and usability COBie spreadsheet in three layers; 1) user interface layer which the user can visualise the COBie data and its capability in terms of a 3D model and dynamic 2D plans, prospective requests of clarifications and building data, 2) data Integration and Process layer which is the core mechanism of VisualCOBie program to translate the COBie spreadsheet to semantic graph-based data which provide the accessibility to facility information and to control its functionalities and to manage the data from database which is visualised in the VisualCOBie platform, and 3) database layer which includes both databases of BIM-based platform and for the graph-database but separately. Several researcher-developed plug-ins in authoring BIM tools which enlarge the implementation of the intrinsic usability of IDM and MVD in BIM software application (Pärn and Edwards, 2017, Farghaly et al., 2018, Heaton et al., 2019). Integration between BIM tool and a web browser which has been conducted by Tang et al. (2020) to illustrate the potential application of BACnet MVD for BAS information exchange (embodied in IFC standard) concerning BIM and FM tools. This integration can leverage the linkage between various parties engaged in the project and BAS software among project lifecycle in terms of data connection from other domains and exchange with various data models. However, there are still some restrictions for data mapping and its implementation tools, which motivate expanding their study to some future goals in terms of encompassing IFC data model and incorporation with other data models. The validation stage confirms that the Building information model accurately includes the information defined in the data exchange requirements and the model view specifications. Several checking routines, named validation rules, are performed at this stage to guarantee that the Building information models are generated and operated correctly. In project validation, data validation tools compare two files: the IFC file of the project (Design Data) and the reference MVD (Constraint Data). Two different approaches are adopted to validate IFC models, which are using IfcDoc (MVDXML checker) and Semantic Web Rules Languages (SWRL). Both Farghaly et al. (2020) and Tang et al. (2020) illustrated the importance of an automatic MVD-based data verification procedure utilising tools like IfcDoc. The IfcDoc tool validates the chosen IFC model alongside the model view concerning the coded and allocated rule categories to the relevant concepts. The embedded feature in IfcDoc allows users to import an IFC instance file and evaluate it according to the defined set of rules coded to the pertinent concepts in the MVD. Other research conducted their validation using implemented quality check tools in BIM platforms such as COBie QC reporter tool (Alnaggar and Pitt, 2019a, Pinheiro et al., 2018b) and KIT EnEff-BIM Converter (Pinheiro et al., 2018b). It is important to note that all the exchange approaches' validation studies have been undertaken at the implementation stage to verify the extraction and integration process; however, none of these studies discuss either the business value of implementing a specific exchange approach or the errors come to light post-implementation. The post-implementation validation tool requires using machine learning techniques to improve validation quality and speed (McArthur et al., 2018).

6. Discussion and Research Directions

The reviewed papers show that digital transformation is the way for effective lean and smart projects in the built environment sector. The review also reveals the evidence of the growing interests in achieving semantic and syntactic interoperability for effective digital transformation. However, the literature about the subject's further development is still limited, with most researches concentrating on achieving Digital Shadow as the integrated digital deliverable. To help bridge this knowledge gap, an integrated framework (Figure 7) is proposed based on ISO 19650 (2018) stages of maturity of analogue and digital information management. The framework provides three stages of Common Data Environment (CDE) and associated layers to improve interoperability in each CDE based on the discussion presented in previous sections. The three CDE are centralised CDE based on standards such as BS 1192, ISO 19650 and DIN SPEC 91391-2, OpenCDE-API initiated by BuildingSMART, and decentralised CDE based on Linked Data Platforms. Four main layers are associated with each CDE; namely, standards layer, technology layer, information layer and business layer, and the integerated digital deliverables are plotted to show what deliverable can be achieved in each stage and associated technology and standards. There is an array of standards that focus on BIM and information management processes within an asset's life cycle; the most comprehensive standards have been developed by BSI and ISO (Lu et al., 2020c). The standard layer in this framework concentrates only on specifications and standards which can enhance the interoperability aspect. In BIM stage, several specifications and standards are adopted to form an effective integration process between BIM and AM data. Also, AM guidelines are utilised in this stage to define the requirements for the development of an asset management system such as ISO 5000 (2012), ISO 5001 and ISO 5002. Other standards are used for syntactic interoperability by defining information data schema to exchange operation-related information throughout an asset's whole life (COBie) such as BS 1192-4. For the transition to OpenBIM stage, new standards were developed (ISO 19650 (2018)) and superseded others (PAS 1192-2 (2013) and PAS 1192-3 (2014)). Others were adopted to reach semantic alignment through the development of classification system within the built environment (ISO 29481-1 (2016)) and syntactic interoperability through Open-source and vendor-neutral exchange format for the example of BIM-related geometry and information (ISO 16739 (2013)). In stage 3, ISO 12006-2 (2015) could be adopted for ontology development within the object-orientated design and PAS 212 to design a system to capture and analyse IoT datasets. The OpenBIM stage lacks an interoperability standard for AECO industry as the developed ones for manufacture sector (ISO 16300 and ISO 15704). As far as the authors' knowledge, there is ongoing work funded by Innovate UK for developing a new industry standard for data sharing which can fit the available gap. Other ongoing research in this area is being conducted by the BIM interoperability expert group’s committee and the Centre of Digital Built Britain (CDBB) and a report has been published in March 2020 for primary and secondary recommendations for effective interoperability in the built environment sector (Moore, 2020).

The technology layer summaries the maturity of the required common data environment (CDE) in each stage and the associated technologies and exchange specifications. In stage 1, the CDE only stores the data and exchanged based on international exchange specifications such as COBie, while in stage 2, more MVDs and automatic rule checking applications are utilised to query, exchange and validate data stored in the CDE. In stage 3, the data in CDE are cross-mapped with other data in other CDEs through using ontology and Linked Data. Information layer presents a type of information in the three stages. It starts with data/models in the authorising tool format, and it could be structured but not mapped to other related data/models. As the expansion of scale and the increase of complexity of construction projects put higher requirements on the level of collaboration among different stakeholders, openBIM approach can meet the needs of information interaction among different software well and improve the efficiency and accuracy of collaboration. BuildingSMART is an open, neutral, and international not-for-profit organisation committed to creating and adopting open, international standards and solutions for infrastructure and buildings. BuildingSMART developed five primary OpenBIM standards namely; IFC, IDM, MVD, BIM Collaboration Format (BCM) and buildingSMART Data Dictionary (bsDD) which can lead to reaching federated information models (Jiang et al., 2019). The last stage requires more than a federated model. It requires considering other datasets outside of the federated model and utilising several information technologies such as BIG Data Analytics and Artificial Intelligence to predict better decisions for operating the asset in object-based server platform.

In general, business value implies to an outcome that is considered advantageous by an organisation, whereas digital transformation initiatives, such as BIM and DT, business value refer to positive effects in the form of benefits generated through the adoption of these initiatives. Identifying DT's adoption benefits is crucial to justify, track, evaluate, and create benchmarks for DT-based investment. In this framework, the business layer consists of six business values (Munir et al., 2020), and they are assigned stages which can provide this value. Despite there is an agreement about the benefits that DT can bring to the AECO sector, there is and will be difficulties in evaluating its business value as it was difficult in BIM too (Munir et al., 2020). Several DT business value evaluation techniques should be developed for achieving successful adoption.

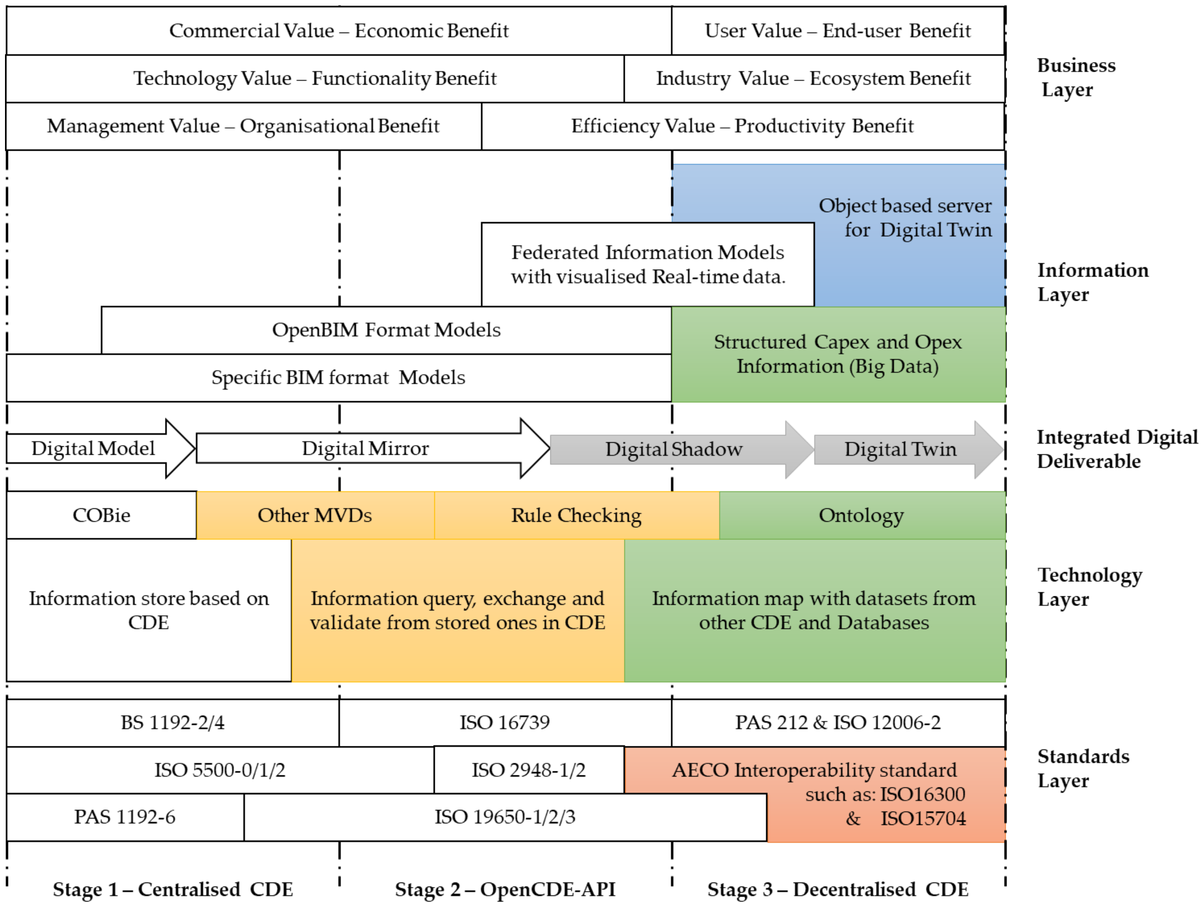

Figure 7: Framework of layers associated with CDE types.

7. Conclusion and Future Work

“The first rule of any technology used in a business is that automation applied to an efficient operation will magnify the efficiency.” (Bill Gates). As Digital Twin is seen as the new benchmark for digitalisation in AECO sector and its automation requires effective integration between datasets stored in several software platforms, interoperability between these software platforms is the first and foremost aspect to achieve for effective implementation of DT initiative. Meanwhile, as BIM is to an extent seen as an analogue to DT in the AECO sector, learning from BIM-AM interoperability could enhance the adoption of DT. To contribute to this, a comprehensive review of the literature in BIM-FM and DT interoperability was conducted in this research.

In this paper, two different classifications were proposed to classify the work done in this area. The first classification – I-IEV framework- groups the interoperability solutions based on four main aspects: identification, integration, exchange and verification. The second classification organises the work done for digital transformation in the AECO sector into four main integrated digital deliverables based on the maturity of data integration; namely, digital model, digital mirror, digital shadow, and digital twin. The second classification rationale is to establish a standard definition of required data integration to reach DT's benefits. The review shows that most of the work done has not reached the level of integration for DT maturity, where the two-way link between the physical and virtual world occurs. It also shows that most of the research concentrates on achieving syntactic interoperability through technology-driven functions and applications and neglecting the semantic enrichment aspect. To advance the adoption of DT in the built environment, our review of the current literature revealed several aspects requires future research: 1) improving semantic enrichment through ontology and Linked data (Pauwels et al., 2015, Lee et al., 2016b, Ferguson et al., 2016, Luiten et al., 2017, Sacks et al., 2020), 2) developing a standard process for data integration between different data sources such as BIM, FM databases, IoT devices and sensors (Alnaggar and Pitt, 2019a, Alnaggar and Pitt, 2019b, Heaton et al., 2019), 3) developing automatic rule checking for exchange data validation (Shalabi and Turkan, 2017, Tang et al., 2020) , 4) utilising BIG Data Analytics to query stored structured and unstructured data (Lu et al., 2020a, Lu et al., 2020d), and 5) evaluating the business value of DT adoption in real case studies (Cavka et al., 2017, Lu et al., 2020a). DT is still in its infancy in the AECO sector and requires the joint efforts of practitioners, government organisation and academics in order to deal with the interoperability challenge and reveal the proposed open research directions that have the potential to yield significant outcomes in the near future.

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