The evolution of ontology in AEC
A two-decade synthesis, application domains, and future directions

Farghaly, Karim; Soman, Ranjith K.; Zhou, Shanjing Alexander

DOI
10.1016/j.jii.2023.100519

Publication date
2023

Document Version
Final published version

Published in
Journal of Industrial Information Integration

Journal of Industrial Information Integration 36 (2023) 100519

Contents lists available at ScienceDirect

Journal of Industrial Information Integration

journal homepage: www.sciencedirect.com/journal/journal-of-industrial-information-integration

The evolution of ontology in AEC: A two-decade synthesis, application domains, and future directions

Karim Farghaly [a,*], Ranjith K. Soman [b], Shanjing Alexander Zhou [a,c,*]

[a] The Bartlett School of Sustainable Construction, University College London, UK
[b] Integral Design & Management Section, Faculty of Civil Engineering & Geosciences, Delft University of Technology, Netherlands
[c] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong

ARTICLE INFO

Keywords:
Interoperability
Building information modelling
Ontology
Semantic web
Linked data
Industry foundation classes (IFC)

ABSTRACT

Ontologies play a pivotal role in knowledge representation, particularly beneficial for the Architecture, Engineering, and Construction (AEC) sector due to its inherent data diversity and intricacy. Despite the growing interest in ontology and data integration research, especially with the advent of knowledge graphs and digital twins, a noticeable lack of consolidated academic synthesis still needs to be addressed. This review paper aims to bridge that gap, meticulously analysing 142 journal articles from 2000 to 2021 on the application of ontologies in the AEC sector. The research is segmented through systematic evaluation into ten application domains within the construction realm- process, cost, operation/maintenance, health/safety, sustainability, monitoring/control, intelligent cities, heritage building information modelling (HBIM), compliance, and miscellaneous. This categorisation aids in pinpointing ontologies suitable for various research objectives. Furthermore, the paper highlights prevalent limitations within current ontology studies in the AEC sector. It offers strategic recommendations, presenting a well-defined path for future research to address these gaps.

1. Introduction

The perception of digital transformation in the Architecture, Engineering, and Construction (AEC) industry has changed dramatically, with greater adoption of information and communication technologies (ICT). This digital transformation era involves implementing several information and automation technologies from other industries, such as Augmented Reality (AR), Virtual Reality (VR), Text Mining, Blockchain and Digital Twin. Despite these technologies, predictive analytics in the AEC industry must catch up to other sectors. Two main challenges must be overcome to achieve predictive analytics: (1) combined, optimal use of topological rule inferencing and machine learning modules for semantic enrichment, (2) encoding representations of building information in forms that are amenable to machine learning [1]. The capabilities of ontologies and Linked Data have shown that they can provide a solution to overcome the mentioned challenges [2].

Knowledge Engineering researchers adopted the term, "ontology" which encompass computational models that enable automated reasoning [3]. One of most appropriate definitions for ontology is "an explicit specification of a conceptualisation" [4]. In general, ontologies have been a part of the Semantic Web Stack to facilitate communication, sharing and annotation of information and reuse of domain knowledge. The application of ontologies with Semantic Web and Linked Data has enjoyed great popularity in other domains, including biology, medical records, cultural heritage, accounting, and social media [5]. These successful cases encourage the implementation of ontologies in the AEC domain [6].

Consequently, there has been abundant research into implementing ontologies to manage information in the AEC sector, resulting in a vast and scattered body of literature [7]. Despite this literature being rich with many significant contributions, most of the existing publications have concentrated on developing new ontologies with new perceptions and ideas rather than reusing existing ontologies and providing objective evidence for their success in implementation (more discussion in Section 4). On the other hand, despite the lack of objective evidence, ontology-based solutions have been seen in the literature as an exceptional approach to achieving interoperability, logic inference, and linking information between domains in the AEC industry [2]. Moreover, ontologies can play a significant role in supporting Explainable Artificial Intelligence (XAI) by providing a clear and structured representation of the domain knowledge that underpins AI systems [8]. For example, in the AEC domain, an ontology could be used to represent the

* Corresponding authors.
E-mail addresses: karim.farghaly@ucl.ac.uk (K. Farghaly), asjzhou@gmail.com (S.A. Zhou).

https://doi.org/10.1016/j.jii.2023.100519

Available online 1 September 2023

various activities, designs, materials, and risks relevant to a particular building design and construction. An AI system could then use this ontology to judge and recommend an effective sustainable design and planning schedule. By providing a clear and structured representation of the domain knowledge, the problem of bias in AI systems can be mitigated, and the AI system can provide a clear and understandable explanation of its decision-making process [9]. To achieve this, the existing ontologies need to be identified and classified based on their application area and maturity of development.

Given the above, the purpose of this paper is to provide a critical review of the existing literature related to ontologies in the AEC industry, emphasising categorisation based on areas of application and their maturity. The remainder of this paper is structured as follows. Section 2 outlines the main objectives of the research. Section 3 explains the research method and the literature retrieval process. Section 4 presents the critical review results by clustering the papers based on their application in the AEC sector. Section 5 provides a discussion and future directions based on the critical review, and finally, Section 6 outlines the conclusion.

2. Research objectives and point of departure

To achieve the research aim, the specific objectives of this review are: (1) provide an overview of the ontologies in the AEC sector literature; (2) categorise the existing research of ontology in the AEC sector based on their area of applications; (3) recommend the future needs and considerations of research in ontology development and mapping in the AEC sector that will bridge identified gaps. Aligned to the paper's objectives, [10] and [2] have conducted critical reviews of semantic web technologies and their applications in the built environment domain, while [7,11] have conducted a scientometric analysis and critical review. [10] developed the clustering based on applications such as scheduling and cost estimation and [11] clustered into three categories: information integration based on ontology, ontology building and ontology application. Meanwhile, [2] developed their clustering based on the benefits of implementation, such as interoperability and linking between domains. Finally, [7] clustered the papers into four groups: domain ontology, Industry Foundation Classes (IFC), automated compliance checking and BIM. As there have been many published articles related to ontologies in the built environment (more than 200 journal articles) since the last review [7], it is crucial to conduct this critical review.

Additionally, as there is a great interest in implementing Digital Twin and integrating construction datasets with real-time datasets, our work will go considerably more in-depth, both in the categorisation based on AEC application and ontology maturity. Fig. 1 summarises the utilised methodology flowchart in this work. After defining the main objectives of the work, the next step is to analyse the state-of-the-art to understand, identify, and track critical trends and ontology applications in the literature. Based on the results, the categorisation of the identified topics was branded. This step helped to identify research gaps and new opportunities in this area of research.

3. Methodology

A critical review of the ontology literature in the AEC domain was performed to achieve the research aim. The review was carried out in three stages: comprehensive literature, literature filtering and content analysis, as shown in Fig. 2.

In Stage 1, Web of Science, a comprehensive citation database, was utilised, and only English-written and peer-reviewed journals were considered. The search was limited to journal articles, which usually provide more comprehensive information and higher-quality contributions. Additionally, the period selected for the search was from 2000 to 2021 to cover recent studies in the last two decades. The following key search phrases were utilised: ((“construction industry") OR ("building project") OR ("construction project") OR ("architecture engineering and construction") OR ("AEC") OR ("civil engineering") OR ("engineering project") OR ("construction project management") OR ("construction management") OR ("BIM") OR ("Digital Twin") OR ("construction management") OR ("asset management")) AND (("ontology") OR ("semantic web") OR ("linked data")). Based on the identified criteria, 302 journal papers were identified. These papers were first imported to Endnote (Reference Manager Software). Subsequently, several queries were performed to ensure no duplications or no conference papers, and books and better understand these articles' distributions from years of publications and sources.

In Stage 2, a thorough evaluation of the 397 papers was conducted. This involved a manual peer review of the titles, abstracts, and keywords by at least two authors to determine their eligibility in addressing the research questions. Additionally, Robotanalyst, a supervised learning system, was employed as a screening tool. Robotanalyst utilises a binary classification model to provide inclusion and exclusion confidence for each paper, which is continuously updated as the screening progresses. To train Robotanalyst, a set of 40 abstracts was manually reviewed and classified as either included or excluded articles. Using this trained model, 183 journal articles out of 397 were identified as relevant references in the first round. A random manual screening of both included and excluded articles was performed to ensure the accuracy of decision-making. In the second round, seven articles were deemed relevant to the research topic, while 41 were irrelevant. In the subsequent third round, one article was found to be appropriate, with one deemed irrelevant. While the authors manually screened abstracts for all 397 papers, using Robotanalyst provided additional benefits. One notable advantage was its ability to cluster abstracts based on various keywords and terms. This facilitated the identification of more relevant references, allowing for a systematic review process. Moreover, using Robotanalyst within a single data environment platform helped streamline the paper review and categorisation process, saving time and effort. In this stage, 149 articles were identified for further analysis.

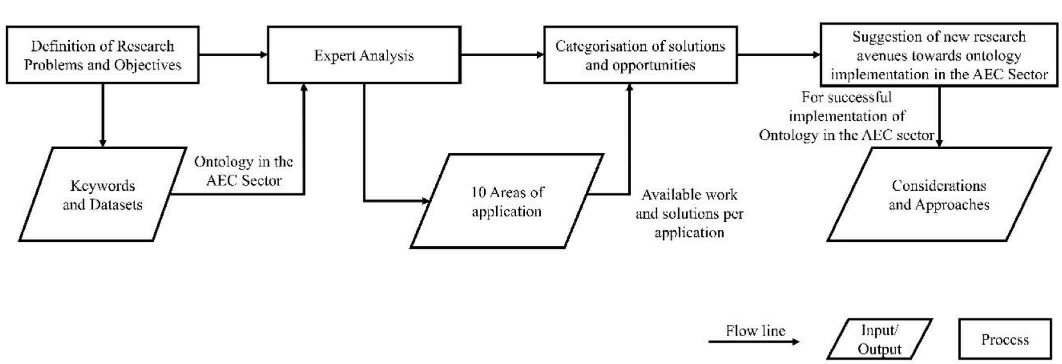

Fig. 1. Methodology flowchart of the research.

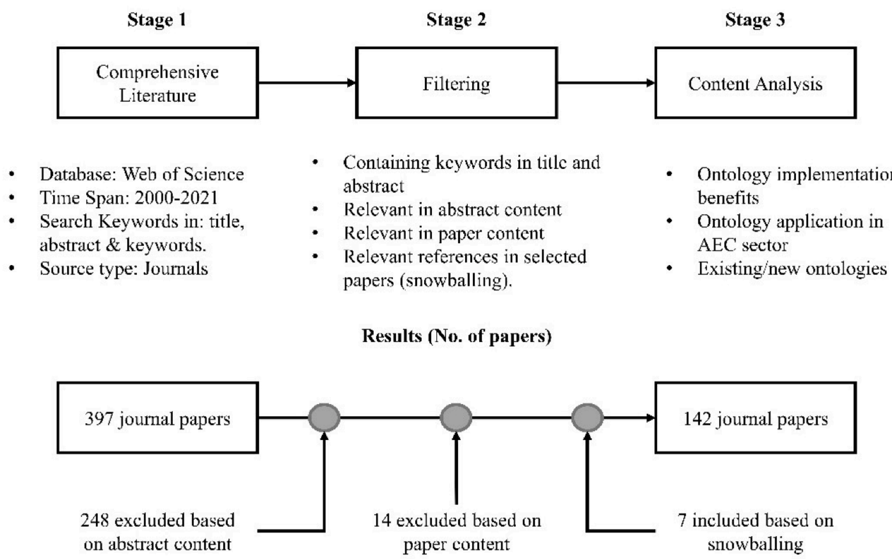

Fig. 2. An overview of the review framework.

The full text of the included papers was downloaded and attached to the relevant EndNote reference. Further, the snowballing technique was utilised to find seven documents in addition to the 149, in which the related papers in the reference sections of the identified papers were reviewed. This technique minimises the likelihood of missing relevant publications. Fourteen papers were excluded as the full text showed they were irrelevant to the research aim stated in the Introduction section. Finally, 142 papers remain after this stage.

In Stage 3, the papers were coded against three classification criteria: benefits, AEC applications, and existing/new ontologies. The benefits classification was based on the three classifications Pauwels et al. [2] suggested: interoperability, logic inference, and linking information between domains. The AEC application classification identified in which aspect of the AEC domain the ontology could be used, such as time, cost, sustainability, and operation and maintenance. The last classification stated whether the used ontology was an existing ontology, or a completely new ontology developed by the authors. The QSR Nvivo 12 platform was used to code the articles against these classifications. The classifications were a mix of concept-driven coding and data-driven coding [12]. The concept-driven coding was used for codes related to benefits, ontological types, and new/existing ontology, while data-driven coding was used for the AEC applications. Fig. 3 shows an example of the codes assigned to the reviewed articles and how they relate to a specific journal paper. It illustrates that eight papers are part of the operation and maintenance category.

Meanwhile, a bibliometric literature review was conducted as the

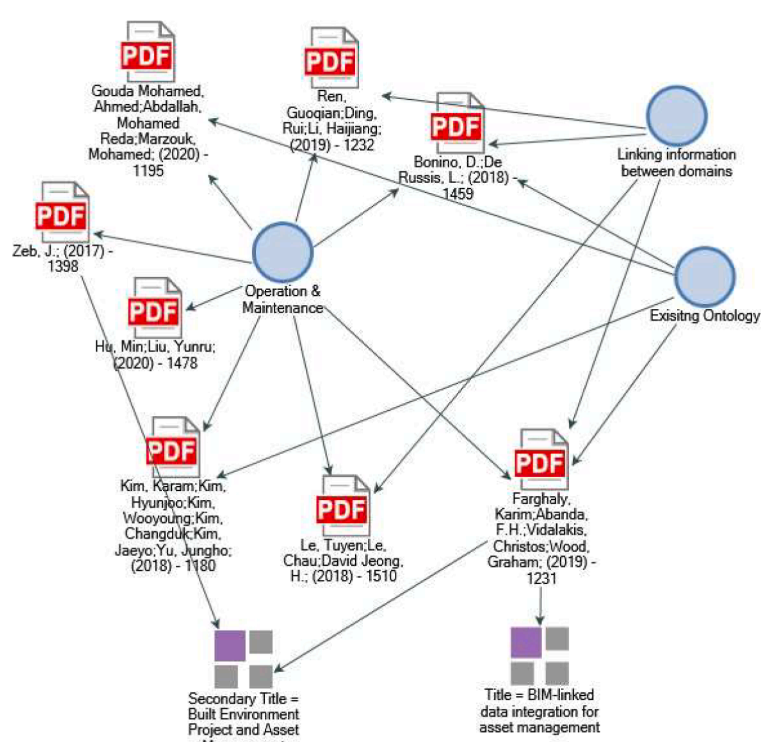

Fig. 3. A screenshot from Nvivo 12 illustrates the codes assigned to the reviewed articles.

statistical method can provide insights for the trends and critical topics through the years of publications, journal sources and co-authorship analysis. Fig. 4 illustrates the distribution of journal articles from 2000 to 2021. The number of papers per year varies with an increase from 2015. The last two years' contribution alone is around 30% of the overall publications, showing a noticeable increase in the implementation of ontological solutions in the AEC sector. Regarding sources, 53 sources were found from the dataset. Automation in Construction is the most cited source with the most publications of 37 journal papers. Then it is followed by the Journal of Computing in Civil Engineering (17 papers) and Advanced Engineering Informatics (10 papers). Finally, a co-occurrence analysis was conducted to identify the predominant topics and keywords within the dataset. The findings of this analysis hold significance for readers, particularly emerging scholars, as they provide insights into the historical progression of ontology implementation in the AEC sector over the years. It is evident that ontologies have consistently emerged as a prominent technology, adapting to the prevailing trends of each era (see Fig. 5). Initially, their focus revolved around engineering and computer sciences, after which they became closely associated with the advent of BIM and its emphasis on interoperability, along with its relationship and complementary nature with Industry Foundation Classes (IFC). Subsequently, ontologies evolved further, aligning with the domain of systems and system of systems, particularly within the realm of infrastructure. Looking ahead, it is anticipated that ontologies in the forthcoming years will increasingly revolve around sustainability as a requirement and digital twins as deliverables, in conjunction with associated technologies such as the Internet of Things (IoT).

4. Applications of ontology-based solutions in the AEC sector

Researchers have developed an array of ontology-based solutions to enhance one or more of the following: interoperability, logic inference, and linking information between domains. These solutions mainly include other digital technologies such as BIM, 4D, GIS, and sensors. This section categorises the solutions based on their applications utilised. Ten main applications were identified: process, cost, operation and maintenance, health and safety, sustainability, monitoring and control, smart cities, heritage building information modelling (HBIM), compliance and finally, miscellaneous. Among these ontology-based solutions, some solutions cover more than one application. For example, the Infrastructure and Construction Process Ontology (IC-PRO-Onto) proposed by [13] covers both process and smart cities applications. Fig. 6 presents the percentage of each application from the total number of reviewed journal papers. Each application and associated ontology-based solutions are discussed in more detail in the following sub-sections.

4.1. Process

Construction processes require information from diverse sources integrated for decision-making, and several ontologies were proposed for the same. Process Specification Language (PSL) is an ontology designed to describe information and facilitate information among manufacturing systems [14]. It can be used to do process planning, production planning, and project management. PSL can describe fundamental concepts of production as it axiomatises a set of intuitive semantic primitives. Specifically, it comprises four disjoint classes (1) activity, (2) activity occurrences, (3) time points, and (4) objects. In the context of construction, [15] presented a constraint ontology to describe processes specific to construction. It defines four abstract types of constraint to describe the relationships between construction processes. These include impeding and enabling constraints to define the role of constraints and flexible and inflexible to define the constraint's flexibility. It does not explicitly reference PSL or other ontologies; however, a limitation of these ontologies is that they do not include different stakeholders' role in the project. To support knowledge-enabled process management and foster coordination among stakeholders, [13] presented a construction-specific domain ontology for processes termed Infrastructure and Construction PRO-cess-Ontology (IC-PRO-Onto). The concepts in IC-PRO-onto are classified into products, actors, constraints, mechanisms, and resources. Although these ontologies represent the construction process in detail and its relations to associated stakeholders, it fails to express how the process is dependent on the constructed product. To inform this dependency of processes to the product it constructs, [16] described classes such as connected to, embedded in, enclosed by, covered by and other relations. These classes help to infer the progress of the construction process when monitored using visual data acquisition methods. Further, to enable synchronous collaboration in construction, a 4DCollab ontology was proposed [17]. These include classes such as session, model, user, and interactive device. From this section, it can be learned that there is no one ontology for defining construction processes; however, the ontologies defined in this section perform a particular set of tasks, and these can be linked and extended to describe the construction purposes for a particular purpose.

4.2. Cost

Cost estimation in the BIM environment requires at least a BIM authoring platform and a specialised cost estimation platform [18]. In other words, despite the 3D models automatically calculating the bill of quantities of material in elements/objects, they do not consider

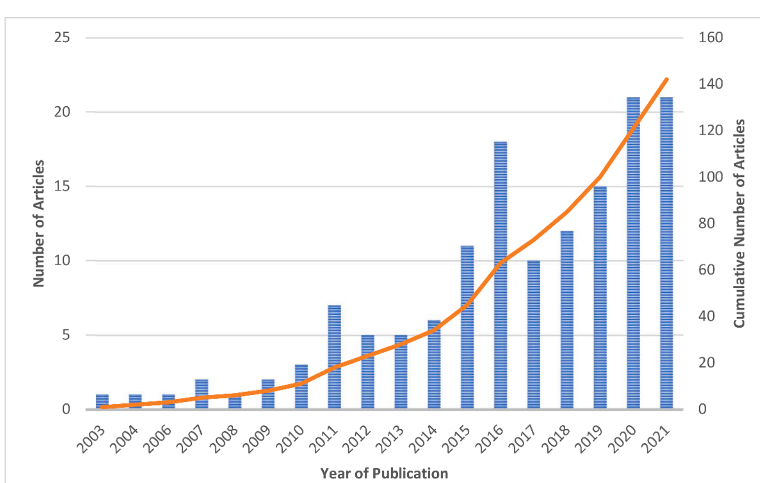

Fig. 4. Number of publications per year among the identified papers (as of October 2021).

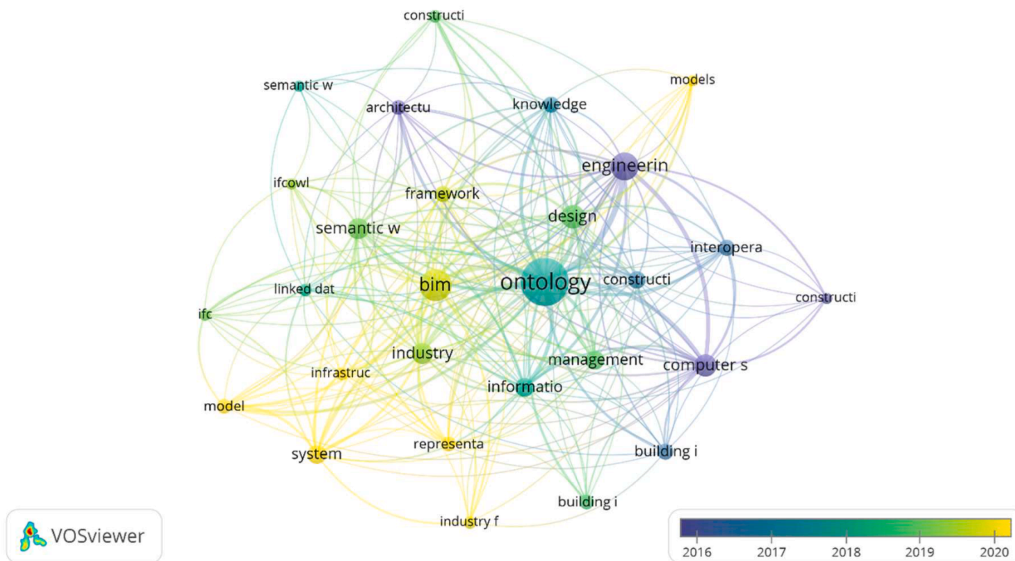

Fig. 5. Network visualisation of co-occurrence analysis for the selected journal papers.

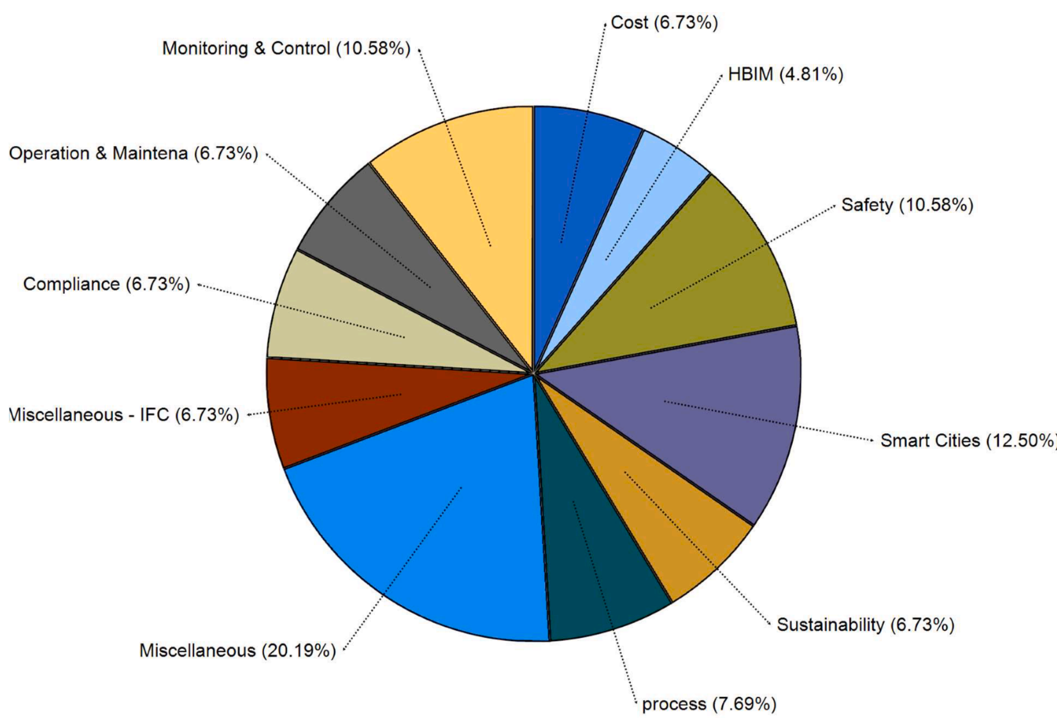

Fig. 6. Journal papers' classification based on their ontology-based application.

information related to construction work [19] and material suppliers' knowledge base [20]. Therefore, the work in this area includes ontologies to map between the different information from BIM and cost estimation platforms. For an effective cost estimation process, both semantic and syntactic data interoperability between the two platforms should be achieved. For semantic interoperability, several ontologies have been developed to create cost estimation knowledge bases. For instance, [21] developed a hierarchical classification and reasoning rules based on the Measurement Specifications of Building Construction and Decoration Engineering taken from GB 50500-2013 (the Chinese national mandatory specifications). At the same time, [18] and [22] utilised the RICS New Rules of Measurement (NRM1) for developing their ontologies. Others developed their ontologies for quantity take-off of specific elements, such as tiles [19] and light-framing building construction [23]. [24] utilised ontology to build a model for knowledge structure of cost estimation in the construction sector. For syntactic interoperability, ontology-based solutions were utilised to improve the exchange between two or more platforms. For instance, some work performed the integration in BIM authoring platforms such as Navisworks and Revit [23], while others developed their own platforms [22, 25].

4.3. Operation and maintenance

Due to the fragmented nature between the Architecture, Engineering, and Construction stages and the Operation and Maintenance (O&M) stage, the required information for O&M during the handover stage is often missing and/or inadequate data as a result of human errors in data collection, entry and analysis. Excessive time and costs are spent to locate and verify the information required from design, planning and construction activities for operating and maintaining the building assets [26]. Even though the IFC schema and its MVDs (Model View Definitions), such as COBie, have been utilised to provide information exchange between BIM and Asset Management (AM) platforms, it still presents many challenges. The IFC schema is a rich and vast data model that can contain the required data for different applications and needs in the AEC and O&M domains. However, facilities managers do not generally use it, since IFC models either do not contain the required information or contain superfluous information, making it difficult to extract the required information [27]. BIM has already been moving in the direction of knowledge processing with the development of IfcOWL, thus leveraging web Linked Data as a tool to extend interoperability to other knowledge domains that were not previously considered. Towards that interoperability, [28] developed several ontologies such as maintenance cost ontology, condition monitoring ontology, and production ontology for better maintenance management of industrial assets with their objects, attributes, and relationships. [29] proposed a framework for sharing construction defect information through the applicability of BIM and Linked Data. They argued that the framework could integrate data in the BIM environment, such as space, element, material, and defect data, including defect types and sources. [30] proposed a method to link the IFC objects with the facilities management work information. They developed a semantic relation between the classes of IFC, COBie, and historical maintenance work concepts. [27] mapped between different AEC and O&M standards and guidelines, such as NRM 1 & 3, Uniclass 2015, and SFG20, to improve the semantic interoperability between BIM and AM platforms. Meanwhile, [31] mapped between different existing ontologies to improve the information exchange for existing buildings. Other researchers developed ontological knowledge bases for the energy consumption of smart cities [32], bridge maintenance [33], the integration of manufacturer product data with the BIM data [34] and maintenance information for existing buildings [35]. Despite the available work to facilitate the integration between BIM and AM, the developed ontologies are still at their conceptual stage and cannot be extensively applied to real-world case studies for better handover to the in-use phase.

4.4. Health and safety

Several ontologies have also been proposed in the literature for sharing safety information and job hazards. For instance, an ontology for job hazard analysis to improve construction safety knowledge management in BIM was proposed by [36]. Other work has been conducted for the same purpose, such as by [37] to link risk knowledge with the related building object in a BIM environment using an ontology-based methodology. They modelled risk knowledge into an ontology-based semantic network, in which a risk map between interdependencies of risks can be inferred semantically. Based on this semantic retrieval mechanism, relevant knowledge can then be dynamically linked to specific objects in the BIM environment. Similarly, a corresponding representation and reasoning framework was proposed by [38], and a domain ontology (SRI-Onto) to retrieve safety risk knowledge in metro construction was developed [39]. Other work includes developing an ontology-based model for proactively predicting the potential for failures and surface subsidence in shield tunnels [40]. [41] employed ontology-based text classification techniques to extract pertinent information from extant construction safety documents. This methodology was aimed at enhancing the drafting of new Job Hazard Analyses (JHA). Subsequent studies [42,43] utilised the formulated ontology to detect and categorise potential hazards inherent in construction images. Most of the developed ontologies related to safety management concentrate on the construction phase with only one or two of the aspects that eventuate the hazard, such as building elements [37], protection systems [44] and activities [39] and neglect other aspects, such as location and scope of work.

4.5. Sustainability

Green construction and green buildings are the expressions of sustainability in the AECO sector, and they have been widely acknowledged in the last two decades. Existing studies have focused on two main topics: to quantify cost and benefits of green construction; and measures to achieve and evaluate green construction. To quantify the cost and benefits of green construction, construction information requires to be integrated and managed differently from the traditional way. [45] proposed an automated process to collect and classify green building material information using web crawling and ontology. The ontology consists of the seven main classes, among which six of them describe the material properties, while the other one is a predefined class based on the material classification system. [46] proposed a framework to manage and query semantic sustainability information from existing ontologies such as SAREF, DogOnt and SSN. Other work adapted BIM and IFC with ontologies to manage sustainability information. These efforts included mapping NRM1 ontology with embodied energy and CO2 to compare environmental impact and cost in the BIM environment [47] and mapping the evaluation indicators of green construction with IFC expression to avoid errors resulting from managing large amounts of construction data [48]. For measures to achieve and evaluate green construction, construction condition ontology was developed for green construction code checking [49,50] and an ontology was developed for capturing the knowledge of green building rating [51].

4.6. Monitoring and control

Monitoring is a field in the AEC domain where semantic web technologies have a significant impact. Linking datasets across multiple domains such as sensors, building information and project management and making logical inferences is critical for monitoring. For example, [52] presented a data fusion ontology to support tasks such as (1) data source identification, (2) data fusion plan generation and (3) synchronisation of spatial and temporal data sources. For a data source, this ontology can describe the level of detail and reference systems for the data items. Similarly, [53] developed an ontology to fuse building's contextual information with data extracted from a smart camera network. Another potential use of ontology for monitoring is to integrate dynamic data with static building data. For example, [54] developed a framework to link the Driver, Needs, Action, and Systems (DNAS) ontology to integrate the dynamic data with a building model to understand occupant behaviour. DNAS ontology was linked to the STriDE model which keeps track of building entities and different relations among them. Another application of ontologies for monitoring is to create a formal representation expert's casual judgment of construction project changes. [55] used three ontologies: (i) Project Profile Ontology (PPO), (ii) Context Sensing Ontology (CSO), and (iii) Change Causality Ontology (CCO) to describe this. PPO describes the context-invariant characteristics and general features associated to a typical construction project, whereas CSO layer represents the "contextual sensitivity" for the causality behind project change events. The CCO describes a contextualised explanation of a fuzzy cognitive mapping used to imitate the intuitive casual judgment of an expert responding to a contextual setting. Although there are specific ontologies for different purposes related to monitoring, most of these ontologies are not linked to other ontologies limiting their capabilities for inferencing. [56] developed a new construction procedural and data collection (CPDC) ontology. The ontology links between planned and executed procedures collected from the construction documents and the sensing tools used in the construction job sites, respectively.

4.7. Smart cities

Research was drawn upon developing ontologies for data schema mappings between domains and infrastructure management in smart cities. Data schema mapping between fields such as devices and surrounding environment, as well as BIM and GIS. For example, DogOnt ontology was initially developed for the home automation domain, then expanded to cover energy modelling between devices and environment from building- towards city- and district-level mappings in smart cities [32]. Several efforts to integrate DogOnt with other ontologies include UCM/MUO for device modelling, and undergoing development to link to positioning ontologies for environment modelling. For mapping data schemas between BIM with GIS domains, an example reference ontology, called semantic city model was developed to map between IFC and CityGML, with potentials to extend to include more schemas [57]. There are other works to develop ontologies for infrastructure and asset management. High-level ontologies for products and processes in infrastructure management include Infrastructure Product Ontology (IPD-Onto) [58], Infrastructure and Construction Process Ontology (IC-Pro-Onto) [13], drill-and-blast tunnelling project [59], utility infrastructure ontology [60], sewer networks [61] and eco-asset ontology (EA-onto) for eco or natural asset management [62]. Other ontologies for specific use cases include Transaction Domain Ontology (Trans_Dom_Onto) for transactions and messages [63], and Tangible Capital Asset Ontology (TCA_Onto) for tangible capital asset reporting [64], and Cats_Onto for the condition assessment of sewer networks [61]. Meanwhile, other research combined, merged and mapped several ontology to achieve infrastructure resilience decision support [65]. They have built the relations between building system ontology, flooding system ontology, underground drainage system and transportation system ontology [65].

4.8. Heritage Building Information Modelling (HBIM)

The Historic/Heritage Building Information Modelling (HBIM) expression was coined in 2009, where it is defined as an approach for developing historic building information models from remotely sensed data which consists of reusable parametric objects [66]. These objects are hosted in a system capable to link/map the objects to survey data such as point clouds and images. In other words, the HBIM models are not seen as only a geometric representation of heritage buildings. However, the HBIM models' components have become advanced objects associated with non-graphical information and relationships with other datasets of historical information [67]. To achieve that semantic enrichment and knowledge mapping, semantic web tools have been utilised to facilitate sharing, integrating, and storing heritage data. There are two different environments to achieve this ontology semantics; namely, BIM platform and connection with external database [67], and newly developed platform based on the developed and reused ontologies [68]. Each of the developed ontologies for HBIM has a different focus such as the development of an ontology based database for vaults [68], the integration of historical buildings maintenance datasets with BIM [69], developing a workflow for mesh-to-HBIM modelling [67] and linking 2D images with 3D models [70,71]. The mentioned approaches show promising results for the semantic enrichment of HBIM models. However, there is still considerable research needed to scale up the examples and develop a reliable system where different purposes can be achieved.

4.9. Compliance

Code compliance is another field where ontologies have a significant impact. Ontologies allow reasoning and ability to infer new knowledge to evaluate for code compliance [72]. Specifically, various explicit and implicit design and operational obligations, prohibitions and permissions need to be reasoned from the applicable norms and requirements to perform code compliance checks. [73] proposed an ontology named 'deontology' to perform code compliance in the AEC domain. It provides a semantic knowledge representation of the knowledge concerning compliance checking. It presents concepts, relations, and deontic axioms. Concepts represent an upper-level description of rules for reasoning. Relations presents the hierarchical and inter-concept relations to represent the interconnections. Deontic axioms represent the definition of the concept in the context of deontology and constraints on their interpretation. Different rule-checking approaches for compliance checking were compared to understand their performance by [74]. Compliance checking has been applied for different purposes. For instance, [75,76] extended multiple ontologies to suite building environmental monitoring and compliance checking. They developed a building information ontology by extending IfcOWL, and developed building regulation ontology to represent knowledge building regulations. [77] proposed a semantic web-based approach towards compliance checking for Building Research Establishment Environmental Assessment Methodology (BREEAM) requirement. Concepts, sub- concepts and their relations were abstracted and modelled as RDF graphs. These covered BREEAM sections such as management, health and wellbeing, energy, and transport. The formalisation of BREEAM requirements was done using conceptual graphs. In another study, [78] modelled the construction constraints using Shapes Constraint Language (SHACL) and used it to check for constraint violations to assist the look ahead planning in construction. All these ontologies used the inferencing capability of semantic web technology to check for rule violations.

4.10. Miscellaneous

More than one application is usually utilised to achieve a specific output/purpose throughout the engineering and management domains of construction. This is mostly associated with the heterogeneity of application models/datasets and the lack of explicitly defined collaboration processes that form interoperability barriers [79]. Several general prototypes and frameworks were proposed in the literature to overcome the interoperability challenge in a general manner rather than for a specific application. This work can be classified into two categories: namely, semantic interoperability and ontologies related to IFC.

4.10.1. Semantic interoperability

In semantic web and linked data category, the work mostly concentrated on optimising the performance in the AEC sector by achieving interoperability between two different platforms. Several approaches were presented on how different sets of information can be captured, linked, queried, and visualised using semantic web and linked data. These approaches could lead to building and construction processes performance optimisation through building energy assessment dashboard [80], identifying occupant issues with building performance through Twitter [81], managing context-sensitive construction information [82], developing an e-commerce platform for industrialised construction procurement [83], semantic representation of BIM data [84,85]. Other work was more general and concentrated on retrieving information. For instance, [86] developed a prototype to enhance the retrieval of information which suggests related search words for the user, while, [87] proposed a filter-based collaboration model where information can be retrieved from the shared design workspace by creating user-defined queries.

On the other hand, in the ontology and other technologies category, other technologies were adapted with ontologies to achieve the interoperability between different platforms and match classes of two or more ontologies and visualise them effectively. For instance, [79] criticised that we cannot enable collaboration between the different phases of the project using only one central project model/database. Therefore, they proposed a multi-model-based management information system, and its backbone is a layered ontology framework. Others utilised semantic vectors with ontologies for facilitating knowledge sharing

[88] and reuse and supporting communication in the AEC sector [89].

4.10.2. Ontologies related to IFC

One of the most used ontologies in the AEC domain is the IfcOWL ontology [90]. IfcOWL is created by lifting Industry Foundation Classes (IFC) in the EXPRESS schema to an ontological level by transforming the concepts in the EXPRESS schema into a terminology Box (TBox). [91] describes the conversion between IFC in EXPRESS to IfcOWL in detail. Since the creation, IfcOWL has been used for a variety of purposes which includes but is not limited to conversion of 3D information to multiple schemas [92,93], semantic rule checking [72], and retrieving implied information [94]. The main disadvantage of IfcOWL is its size as it reduces its usability. Users may not need all the classes in IfcOWL, yet they must understand it before it can be effectively used. This disadvantage has led to the creation of smaller and modular ontologies such as Building Topology Ontology (BOT) [95]. Another ontology based on IFC is the IDM ontology [96]. IDM ontology was created to demonstrate an ontology-based approach for developing data exchange requirements and model views for Building Information Modelling (BIM).

5. Discussion

5.1. Findings discussion

The findings section reviewed ontology-based solutions applied in the AEC sector. It categorised these solutions into 10 application areas: process, cost, operation/maintenance, health/safety, sustainability, monitoring/control, smart cities, heritage building information modelling (HBIM), compliance, and miscellaneous. Several ontologies have been developed for construction processes, cost estimation, sustainability evaluation, safety management, smart city data integration, and compliance checking. The findings section goes beyond summarizing existing literature to provide critical analysis of limitations in current ontologies, including lack of real-world validation and interoperability gaps between siloed ontologies. While past reviews identify broad research themes [2,7], the detailed examples here showcase the breadth of ontology uses cases throughout the construction life cycle. Furthermore, it offers suggestions to address challenges noted in prior reviews, including the selection of suitable ontology development techniques [11], handling of semantic connections [2], and unified implementation endeavours [10]. The critique on the conceptual nature of most existing ontologies, and the need for integrated ontologies covering design to operations, provides unique insights. The findings not only review the state of the art but extract specific opportunities for more impactful research that can enable greater industry adoption.

5.2. Considerations for future ontology-based solutions

Considering the following issues in future research could help move ontology-based solutions toward full-scale mainstream acceptance and regular use, which has been difficult to achieve so far.

5.2.1. New ontologies vs extension of existing ontologies

Most of the ontologies in the construction sector are aimed at fulfilling a particular aim. There are two approaches which could be used to achieve this aim, which are (1) creating a new ontology such that it describes all the concepts and relationships required for achieving the aim, and (2) creating an extension for an existing ontology so that limitation of an existing ontology to perform a task may be addressed through this extension. [77] followed the first approach where they developed an ontology to support compliance checking of BREEAM where every concept required for the compliance checking was modelled into the ontology. Others followed the same approach for developing an ontology for construction knowledge (DOCK) [97] construction-oriented product [98], sewer networks [61] and building regulation [99]. Whereas [78] follows the second approach where they presented LinkOnt ontology which is used to describe specific process related characteristics which cannot be easily inferred using existing IfcOWL [90]. Also others followed the same and built their ontologies based on available ones or available classifications such as: NRM [18], Uniclass2 [27], IfcOWL [91,100,101], and BIMSO [85]. These two approaches are analogous to the development of tools. Either by developing an add-in to a software to perform a particular task or creating a new software altogether. Both methods have its advantages and disadvantages [31].

Creating a new ontology may have an advantage as it enables creating concepts and relations tailored to the developer/user needs whereas it is not as easy while extending an ontology. However, when numerous ontologies are created, it is difficult to manage them, and the problems of interoperability arise. There are several compelling reasons why utilising existing ontologies is often preferable to creating new ones such as reusability and interoperability, consistency and standardization, time and cost efficiency and integration with existing systems and datasets. Therefore, it would be beneficial that researchers check the existing ontologies and develop their work taking them into consideration. [11] highlighted that the alignment of most of the small ontologies would be ideal and it would take time. Unfortunately, the AEC scholar has not started yet in the process of the alignment. To contribute in that, Table 1 summarises the main existing ontologies and their domains. The Digital Construction Ontology (DIC) and Smart Energy Aware Systems Ontology (SEAS) ontology consists of several ontologies which cover several domains. Scholars can reuse them and add to them to achieve their research goals and objectives.

5.2.2. Large vs small ontologies

The ontologies in the construction sector vary in sizes. There are large ontologies which cater to many tasks. For example, IfcOWL has its origin from EXPRESS language and can be tailored to perform many tasks, which include but are not limited to design, construction, operation, and rule checking [72,94,102,103]. However, a problem with such large ontologies is modularity. They are so large with more than 1000 classes (IfcOWL for IFC4_ADD2 consists of 1331 classes and 1599 properties). Large size makes it difficult to be understood by the developers who are looking towards extending it and tend not to use it [31]. On the other side of the spectrum, there are smaller and modular

Table 1
Existing ontologies suitable for reuse in the AEC sector.

Name	Prefix	Domain
Digital Construction	dic	https://digitalconstruction.github.io/v/0.3/index.html
Building Topology Ontology	bot	https://w3c-lbd-cg.github.io/bot/
Building Product Ontology	bpo	https://www.projekt-scope.de/ontologies/bpo/
IFC Ontology	ifcOWL	https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL
Data Catalog Vocabulary	DCAT	https://www.w3.org/TR/vocab-dcat-2/#UML_DCAT_All_Attr
Brick Ontology	brick	https://brickschema.org/ontology/1.2
Event Ontology	event	http://motools.sourceforge.net/event/event.html
SemanticBIM Ontology	sbim	http://www.semanticbim.com/ontologies/residentialBuilding.owl
Smart Energy Aware Systems Ontology	seas	https://ci.mines-stetienne.fr/seas/
VOAF	voaf	https://lov.linkeddata.es/vocommons/voaf/v2.3/
FOAF	foaf	http://xmlns.com/foaf/spec/
VANN	vann	https://vocab.org/vann/
Quantities, Unit, Dimensions and Types	qudt	http://qudt.org/2.1/schema/qudt
Organisation Ontology	Org	https://www.w3.org/TR/vocab-org/
Time Ontology	Time	https://www.w3.org/2006/time

ontologies such as BOT [104,105] Smaller ontologies cater to a specific task and are easy to understand as there are lesser number of classes. Even though it is easy to extend, there exists a challenge on how to define and manage semantic links during the extension of these ontologies. One of the main limitations in most of the work done in ontology-based solutions in the AEC sector is that they identify new and small ontology for a specific purpose. Despite the authors state that the developed ontologies are extendable, and they can be applied for a bigger sample/dataset, they have never been extended. That is mainly because the ontologies are not shared with the research community. Communities such as Linked Building Data Group should encourage researchers to share their ontologies with other scholars, this could lead to better collaboration, decrease repetitive work and enhance the implementation of ontological solutions in the AEC sector.

5.2.3. Towards an ontology search engine for AEC

According to [106], the deficiencies in existing ontologies are the main obstacles to reuse these ontologies. Reusability is one of the main principles to be followed while developing an ontology. This requires extensive search of the existing ontologies to find classes and TBox items that may be reused in the new ontology/extension ontology. However, most of the construction ontologies are not published in the public domain, except for a few such as IfcOWL and BOT. Therefore, redundant ontologies are being created by researchers for example in the health and safety sector there are four different developed ontologies which can be merged as they fit the same purpose [37,42,107,108]. Based on our review, we have observed that alignment with only a limited number of other ontologies is commonly indicated on the publication page of existing ontologies. The current alignment approach fails to capture the secondary relationships between ontologies, such as how the digital construction and brick ontologies can be mapped using the IFC ontology. Search engines for ontologies specific to the AEC domain can be a valuable resource for researchers, developers, and other stakeholders who need to work with ontologies in the built environment sector. Such a search engine can help users find relevant ontologies quickly and efficiently, saving them time and effort in searching for and evaluating ontologies manually. In addition to providing a list of ontologies, a search engine can also show the relationships between different ontologies, including how they relate to each other and how they can be integrated to create a more comprehensive ontology for the domain. This can help users make more informed decisions about which ontologies to use and how to combine them effectively. This led us to the need of a public domain database/search engine for ontologies such as [109] to cater to AEC researcher's needs. It would be beneficial to combine the research projects available and well-define their purposes and aspects covered. The search engine can contain the existing projects such as the one presented in Table 2.

5.2.4. Ontology merging and mapping

Mapping new ontologies to existing ontologies is a crucial step to gaining from the power of the Semantic Web. Ontologies mapping is defined in [110] as "the task of relating the vocabulary of two ontologies that share the same domain or discourse in such a way that the mathematical structure of ontological signatures [...] is respected." Two broad approaches address the mapping of ontologies:

- Ontology Merging, which consists in merging all the considered ontologies into a single one [111]. For enhancing project scope management, [112] developed an ontology to integrate the datasets of work breakdown structures (WBS) and cost breakdown structure (CBS). This provides an environment to develop WBSs based on CBS, allowing both clients and contractors to develop the schedule based on the construction units level (the units of quantity survey contracts). The work done in ontology merging performs a syntactic and semantic merge by resulting in a single ontology representing the integrated abstract syntaxes of all the considered domains. This area requires much attention by researchers to merge the available ontologies of a specific application. Although, understandably, not every aspect/class can be merged and included in one ontology for each application, the authors believe many of the classes can be included and would be sufficient for most of the purposes. Also, the developed central ontology can be extended further for specific purposes.
- Semantic Bridges, which concentrates on the definition of semantic mappings between the considered domains. Semantic bridges are utilised when one singular reference representation can be utilised to describe a class in different ontologies. [101] proposed utilising BOT ontology as a building reference ontology to connect building and geospatial geometry. This approach was utilised since software applications are commonly built on different geometry kernels, producing inaccuracies when transferring complex, mathematical geometry descriptions from one application to the other. Other work proposed developing several ontologies based on available standards such as Uniclass2 and NRM 1&3 to cross map the datasets in BIM and asset management platforms [27]. For heat loss calculation, [95] developed an Ontology for Property Management (OPM) and proposed a semantic bridge with a project specific extensions of the Building Topology Ontology (BOT). The work done in sematic bridges perform only semantic alignment of the considered domains. This area also needs much attention from researchers as it is vital factor for interoperability in the Digital Twin era such as building bridge between IfcOWL and Semantic Sensor Network Ontology (SSN) [113].

5.2.5. Green building lifecycle and circularity

Sustainability and circularity are currently the driving forces in the built environment sector. Numerous initiatives are underway worldwide to encourage companies to adopt circular practices, such as the work carried out in Europe regarding EU taxonomy [114]. Undoubtedly, ontologies can play a crucial role in advancing green building and circularity in the built environment. Ontologies can facilitate communication and collaboration among stakeholders in the built environment, including architects, engineers, builders, and policymakers. For example, ontologies can be used to model the various components of green buildings in existing material and building passports, including energy systems, water management, and waste reduction strategies. This can help stakeholders to identify and address sustainability issues more effectively, leading to more efficient and environmentally friendly buildings. Similarly, ontologies can be used to model the various materials and components used in building construction and maintenance, enabling stakeholders to identify opportunities for reuse, recycling, and repurposing of materials. In summary, ontologies hold significant potential for fostering sustainable and circular practices in the built environment by providing a common language and framework for effective communication and collaboration. However, it is essential to consider the aforementioned recommendations and take them into account to fully realise these benefits.

Table 2
Existing research projects based on ontological solutions in the AEC sector.

Name	Domain
BIM4REN	https://bim4ren.eu/
BIM-SPEED	https://www.bim-speed.eu/en -
BIMERR	https://bimerr.eu/
BIM4EEB	https://www.bim4eeb-project.eu/
BIMProve	https://www.bimprove-h2020.eu/
CBIM	https://cbim2020.net.technion.ac.il/
BIM2TWIN	https://bim2twin.eu/
COGITO	https://cogito-project.eu/
ASHVIN	https://www.ashvin.eu/
SPHERE	https://sphere-project.eu/

5.2.6. Ethical considerations

There are several ethical considerations that need to be taken into account when using, implementing, and developing ontology in the AEC sector. Firstly, it is crucial to ensure that the ontology used is unbiased and free from any discriminatory elements. This is particularly important in the AEC sector, as the use of biased ontology could result in the exclusion of certain groups or individuals from opportunities and resources. To address this concern, collaborative efforts between industry and academia are necessary to update existing open-source formats like IFC (Industry Foundation Classes) and reduce dependence on proprietary software formats provided by individual software vendors. By working together, we can ensure a more inclusive and equitable foundation for the AEC sector. Secondly, the privacy and security of data need to be considered when implementing and developing ontology. AEC projects often involve sensitive and confidential information, and it is essential to ensure that the ontology system used is secure and that data is only accessible to authorized parties. Existing guidelines and policies, such as the General Data Protection Regulation (GDPR) in the European Union, provide a framework for achieving data protection and security standards. By adhering to such regulations and implementing robust security measures, we can ensure the confidentiality and integrity of data within the ontology system. Thirdly, transparency is crucial when using ontology in the AEC sector. It is essential to be open about the ontology's purpose, design, and functionality to ensure that all stakeholders are aware of how the system works and how their data is being used. Fourthly, it is important to ensure that the ontology used is up-to-date and relevant. Outdated or irrelevant ontology could lead to incorrect decisions being made, which could have significant consequences for AEC projects. Finally, it is important to consider the broader societal implications of the ontology employed.

5.3. Limitations of the present paper

The results of this review may have been affected by several limitations. Firstly, the selection of primary studies may have been subject to bias due to the subjective assessment criteria. However, the authors took several measures to minimise this risk, including discussing any discrepancies in selection and using popular search engines and snowballing techniques. Secondly, the study may have missed out those ontology-based solutions that have been implemented in the AEC sector but have not been published due to copyright reasons. Thirdly, most of the developed ontologies are not published in RDF/OWL format, making it difficult for the authors to compare them quantitatively and evaluate their maturity. As a result, the evaluation in this research was based on published papers rather than the ontology-based solutions themselves.

6. Conclusion

6.1. Overall conclusion

Over the past decade, the AEC sector has seen a significant surge in research directed towards ontology development, especially concerning the creation of digital twins for construction and the operational phase of built environment assets. This research trajectory aimed to integrate data from disparate sources, often with ambiguous and overlapping semantics. With the examination of 142 papers, two distinct approaches emerged concerning ontology development: creating entirely new ontologies to fulfil objectives aims or extending existing ones to address limitations. For instance, there are some researchers who have built new ontologies for construction knowledge, sewer networks, and building regulations, among other specific objectives. Conversely, some have based their work on existing ontologies or classifications, such as NRM, Uniclass2, and IfcOWL. This trend is reminiscent of the general software development paradigm – either to develop new software or to create an add-on to existing software. While new ontologies offer the advantage of tailored concepts, they can pose challenges related to interoperability when many of them emerge. On the other hand, using existing ontologies offers benefits but might not cater to unique needs. Thus, there is a distinct need for a balance between the two approaches.

6.2. Theoretical contribution

Over the recent years, the scholarly community has observed an upswing in research endeavours centered on ontologies and data integration, a trend that seems to be parallel with the evolving acceptance of digital twins in various sectors. Nevertheless, there appeared to be a notable absence of a systematic synthesis, which often serves as the bedrock for consolidating academic knowledge in such emerging fields. Addressing this void, the present paper presents an extensive review and subsequent synthesis of the research focused on linked data and semantic web technologies. Through methodical exploration, we have categorized this body of work into 10 pertinent application domains specific to the construction sector. In this light, future academics and practitioners aiming to delve into ontology-related ventures can potentially lean on this paper as a foundational reference.

It not only facilitates the identification of relevant ontologies tailored to specific research goals, whether it pertains to refining existing models or pioneering novel ontologies, but also encapsulates the nuances of the field. Importantly, our rigorous examination has spotlighted certain limitations that are inherent to the prevailing ontology-based research in the sector. In response, we proffer judicious recommendations, thereby laying down a roadmap for subsequent research, aiming to navigate and address these identified constraints. Key recommendations for future AEC ontology research and development include:

- Extending Existing Ontologies: While crafting a new ontology may seem more straightforward and occasionally more effective, researchers should primarily build upon and extend existing ontologies. This approach prevents the accumulated knowledge and expertise creating these original ontologies from wastage.
- Building Modular Ontologies: Instead of constructing large, cumbersome ontologies, the emphasis should be on developing smaller, modular ontologies. This not only makes mapping and merging easier but also ensures they are adaptable across various applications.
- Publishing Ontologies Publicly: There's an urgent need for ontologies to be accessible and shared in the public domain. Alongside their publication, detailed documentation of the concepts and relationships should be made available to reduce the current trend of researchers creating new ontologies rather than reusing the existing ones.
- Ontology Search Engine: An ontology search engine, akin to web search engines, would significantly bolster the reuse of ontologies. Such a tool would scan published ontologies, maintaining real-time data on the latest developments, enabling users to discover pertinent ontologies via keyword searches.

6.3. Practical contribution

This comprehensive review serves as a foundational resource for both academic scholars and industry professionals, providing insights into ontology development, applications, and challenges. Professionals and researchers can utilise this paper as a preliminary reference to pinpoint relevant ontologies for their projects. The overarching objective is to foster the integration of ontologies within the AEC domain, paving the way for a more insightful and informed construction sector, especially with the introduction of platforms like the Digital Data Decision Room (D3R) on construction sites. However, this study does have its limitations, being confined solely to the AEC sector and not having access to many non-public ontologies. As we step into the Digital Twin era, it's crucial to consider expanding the scope to encapsulate real-time data, Internet of Things (IoT), and sensor-related ontologies. Given the inaccessibility of many ontologies, future research should heavily focus on developing a dedicated search engine for AEC ontologies. Despite its limitations, this research stands as a solid guidepost for individuals seeking to understand and implement ontology-based solutions in the AEC domain.

Declaration of Competing Interest

The authors declare that: All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version. This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript. The following authors have affiliations with organizations with direct or indirect financial interest in the subject matter discussed in the manuscript:

Data availability

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

Acknowledgement

The project has been kindly sponsored by Innovate UK grants AEC Production Control Rooms No. 106169.

References

[1] R. Sacks, M. Girolami, I. Brilakis, Building information modelling, artificial intelligence and construction tech, Develop. Built Environ. (2020), 100011, https://doi.org/10.1016/j.dibe.2020.100011.

[2] P. Pauwels, S. Zhang, Y.-C. Lee, Semantic web technologies in AEC industry: a literature overview, Autom. Constr. 73 (2017) 145–165, https://doi.org/10.1016/J.AUTCON.2016.10.003.

[3] P. Spyns, R. Meersman, M. Jarrar, Data modelling versus ontology engineering, SIGMOD Record (2002) 12–17, https://doi.org/10.1145/637411.637413.

[4] R. Neches, R. Fikes, T. Finin, T. Gruber, R. Patil, T. Senator, W.R. Swartout, Enabling technology for knowledge sharing, AI Magaz. 12 (1991) 36–56.

[5] M. Schmachtenberg, C. Bizer, H. Paulheim, Adoption of the linked data best practices in different topical domains, Semantic Web - ISWC 2014 8796 (2014) 245–260. Pt I.

[6] F. Radulovic, M. Poveda-Villalón, D. Vila-Suero, V. Rodríguez-Doncel, R. García-Castro, A. Gómez-Pérez, M. Poveda-Villalon, D. Vila-Suero, V. Rodriguez-Doncel, R. Garcia-Castro, A. Gomez-Perez, Guidelines for Linked Data generation and publication: an example in building energy consumption, Autom. Constr. 57 (2015) 178–187, https://doi.org/10.1016/j.autcon.2015.04.002.

[7] B. Zhong, H. Wu, H. Li, S. Sepasgozar, H. Luo, L. He, A scientometric analysis and critical review of construction related ontology research, Autom. Constr. 101 (2019) 17–31, https://doi.org/10.1016/j.autcon.2018.12.013.

[8] A. Barredo Arrieta, N. Díaz-Rodríguez, J. Del Ser, A. Bennetot, S. Tabik, A. Barbado, S. Garcia, S. Gil-Lopez, D. Molina, R. Benjamins, R. Chatila, F. Herrera, Explainable Artificial Intelligence (XAI): concepts, taxonomies, opportunities and challenges toward responsible AI, Aktuel. Aspekte Kernfusionsforsch., Informationstag. 58 (2020) 82–115, https://doi.org/10.1016/j.inffus.2019.12.012.

[9] J.M. Rožanec, B. Fortuna, D. Mladenić, Knowledge graph-based rich and confidentiality preserving Explainable Artificial Intelligence (XAI), Aktuel. Aspekte Kernfusionsforsch., Informationstag. 81 (2022) 91–102, https://doi.org/10.1016/j.inffus.2021.11.015.

[10] F.H. Abanda, J.H.M. Tah, R. Keivani, Trends in built environment semantic web applications: where are we today? Expert Syst. Appl. 40 (2013) 5563–5577, https://doi.org/10.1016/j.eswa.2013.04.027.

[11] Z. Zhipeng, G.Y. Miang, S. Lijun, Overview and analysis of ontology studies supporting development of the construction industry, J. Comput. Civil Eng. 30 (2016), 4016026, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000594.

[12] B. Edhlund, A. McDougall, NVivo 12 essentials, Lulu. com (2019).

[13] N.M. El-Gohary, T.E. El-Diraby, Domain ontology for processes in infrastructure and construction, J. Constr. Eng. Manag. 136 (2010) 730–744, https://doi.org/10.1061/(asce)co.1943-7862.0000178.

[14] M. Grüninger, C. Menzel, The process specification language (PSL) theory and applications, AI Magaz. 24 (2003) 63–74.

[15] B. Koo, M. Fischer, J. Kunz, Formalization of construction sequencing rationale and classification mechanism to support rapid generation of sequencing alternatives, J. Comput. Civil Eng. 21 (2007) 423–433, https://doi.org/10.1061/(ASCE)0887-3801(2007)21:6(423).

[16] K.K. Han, D. Cline, M. Golparvar-Fard, Formalized knowledge of construction sequencing for visual monitoring of work-in-progress via incomplete point clouds and low-LoD 4D BIMs, Adv. Eng. Inf. 29 (2015) 889–901, https://doi.org/10.1016/j.aei.2015.10.006.

[17] C. Boje, V. Bolshakova, A. Guerriero, S. Kubicki, G. Halin, Semantics for linking data from 4D BIM to digital collaborative support, Front. Eng. Manage. (2020), https://doi.org/10.1007/s42524-020-0111-7.

[18] F.H. Abanda, B. Kamsu-Foguem, J.H.M. Tah, BIM New rules of measurement ontology for construction cost estimation, Eng. Sci. Technol. Int. J. 20 (2017) 443–459, https://doi.org/10.1016/j.jestch.2017.01.007.

[19] S.K. Lee, K.R. Kim, J.H. Yu, BIM and ontology-based approach for building cost estimation, Autom. Constr. 41 (2014) 96–105, https://doi.org/10.1016/j.autcon.2013.10.020.

[20] M. Niknam, S. Karshenas, Integrating distributed sources of information for construction cost estimating using Semantic Web and Semantic Web Service technologies, Autom. Constr. 57 (2015) 222–238, https://doi.org/10.1016/j.autcon.2015.04.003.

[21] X. Liu, Z. Li, S. Jiang, Ontology-based representation and reasoning in building construction cost estimation in China, Future Internet 8 (2016) 39, https://doi.org/10.3390/fi8030039.

[22] G. Ren, H. Li, R. Ding, J. Zhang, C. Boje, W. Zhang, Developing an information exchange scheme concerning value for money assessment in public-private partnerships, J. Build. Engineering 25 (2019), 100828, https://doi.org/10.1016/j.jobe.2019.100828.

[23] H. Liu, M. Lu, M. Al-Hussein, Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry, Adv. Eng. Inf. 30 (2016) 190–207, https://doi.org/10.1016/j.aei.2016.03.001.

[24] H. Im, M. Ha, D. Kim, J. Choi, Development of an ontological cost estimating knowledge framework for EPC projects, KSCE J. Civ. Eng. 25 (2021) 1578–1591, https://doi.org/10.1007/s12205-021-1582-8.

[25] M. Hu, Y. Liu, E-maintenance platform design for public infrastructure maintenance based on IFC ontology and semantic web services, Concurr. Comput. 32 (2020) e5204, https://doi.org/10.1002/cpe.5204.

[26] P. Teicholz, others, BIM for facility managers, John Wiley & Sons, 2013.

[27] K. Farghaly, F.H. Abanda, C. Vidalakis, G. Wood, BIM-linked data integration for asset management, Built Environ. Project Asset Manage. 9 (2019) 489–502, https://doi.org/10.1108/bepam-11-2018-0136.

[28] J. Zeb, An eco asset ontology towards effective eco asset management, Built Environ. Project Asset Manage. 7 (2017) 388–399, https://doi.org/10.1108/BEPAM-11-2016-0061.

[29] D.-Y.Y. Lee, H. lin Chi, J. Wang, X. Wang, C.-S.S. Park, A linked data system framework for sharing construction defect information using ontologies and BIM environments, Autom. Constr. 68 (2016) 102–113, https://doi.org/10.1016/j.autcon.2016.05.003.

[30] K. Kim, H. Kim, W. Kim, C. Kim, J. Kim, J. Yu, Integration of ifc objects and facility management work information using Semantic Web, Autom. Constr. 87 (2018) 173–187, https://doi.org/10.1016/j.autcon.2017.12.019.

[31] F. Sadeghineko, B. Kumar, Application of semantic Web ontologies for the improvement of information exchange in existing buildings, Constr. Innov.-England (2021), https://doi.org/10.1108/CI-03-2021-0058.

[32] D. Bonino, L. De Russis, DogOnt as a viable seed for semantic modeling of AEC/FM, Semantic Web 9 (2018) 763–780, https://doi.org/10.3233/SW-180295.

[33] G. Ren, R. Ding, H. Li, Building an ontological knowledgebase for bridge maintenance, Adv. Eng. Softw. 130 (2019) 24–40, https://doi.org/10.1016/j.advengsoft.2019.02.001.

[34] M. Niknam, F. Jalaei, S. Karshenas, Integrating BIM and product manufacturer data using the semantic web technologies, J. Inform. Technol. Constr. 24 (2019) 424–439, https://doi.org/10.36680/j.itcon.2019.022.

[35] A. Gouda Mohamed, M.R. Abdallah, M. Marzouk, BIM and semantic web-based maintenance information for existing buildings, Autom. Constr. 116 (2020), 103209, https://doi.org/10.1016/j.autcon.2020.103209.

[36] S. Zhang, F. Boukamp, J. Teizer, Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA), Autom. Constr. 52 (2015) 29–41, https://doi.org/10.1016/j.autcon.2015.02.005.

[37] L.Y. Ding, B.T. Zhong, S. Wu, H.B. Luo, Construction risk knowledge management in BIM using ontology and semantic web technology, Saf. Sci. 87 (2016) 202–213, https://doi.org/10.1016/j.ssci.2016.04.008.

[38] H.-H.H. Wang, F. Boukamp, Ontology-based representation and reasoning framework for supporting job hazard analysis, J. Comput. Civil Eng. 25 (2011) 442–456, https://doi.org/10.1061/(asce)cp.1943-5487.0000125.

[39] X. Xing, B. Zhong, H. Luo, H. Li, H. Wu, Ontology for safety risk identification in metro construction, Comput. Ind. 109 (2019) 14–30, https://doi.org/10.1016/j.compind.2019.04.001.

[40] J. Du, R. He, V. Sugumaran, Clustering and ontology-based information integration framework for surface subsidence risk mitigation in underground tunnels, Cluster Comput. 19 (2016) 2001–2014, https://doi.org/10.1007/s10586-016-0631-4.

[41] N.W. Chi, K.Y. Lin, S.H. Hsieh, Using ontology-based text classification to assist job hazard analysis, Adv. Eng. Inf. 28 (2014) 381–394, https://doi.org/10.1016/j.aei.2014.05.001.

[42] B. Zhong, H. Li, H. Luo, J. Zhou, W. Fang, X. Xing, Ontology-based semantic modeling of knowledge in construction: classification and identification of hazards implied in images, J. Constr. Eng. Manag. 146 (2020), 4020013, https://doi.org/10.1061/(asce)co.1943-7862.0001767.
[43] W.L. Fang, L. Ma, P.E.D. Love, H.B. Luo, L.Y. Ding, A.O. Zhou, Knowledge graph for identifying hazards on construction sites: integrating computer vision with ontology, Autom. Constr. 119 (2020), https://doi.org/10.1016/j.autcon.2020.103310.
[44] B.H.W. Guo, Y.M. Goh, Ontology for design of active fall protection systems, Autom. Constr. 82 (2017) 138–153, https://doi.org/10.1016/j.autcon.2017.02.009.
[45] S.H. Hong, S.K. Lee, J.H. Yu, Automated management of green building material information using web crawling and ontology, Autom. Constr. 102 (2019) 230–244, https://doi.org/10.1016/j.autcon.2019.01.015.
[46] E. Petrova, P. Pauwels, K. Svidt, R.L. Jensen, Towards data-driven sustainable design: decision support based on knowledge discovery in disparate building data, Archit. Eng. Design Manage. 15 (2019) 334–356, https://doi.org/10.1080/17452007.2018.1530092.
[47] F.H. Abanda, A.H. Oti, J.H.M. Tah, Integrating BIM and new rules of measurement for embodied energy and CO2 assessment, J. Build. Eng. 12 (2017) 288–305, https://doi.org/10.1016/j.jobe.2017.06.017.
[48] Z. Xu, X. Wang, W. Zhou, J. Yuan, Study on the evaluation method of green construction based on ontology and BIM, Adv. Civil Eng. 2019 (2019) 20, https://doi.org/10.1155/2019/5650463.
[49] S. Jiang, N. Wang, J. Wu, Combining BIM and ontology to facilitate intelligent green building evaluation, J. Comput. Civil Eng. 32 (2018), 04018039, https://doi.org/10.1061/(asce)cp.1943-5487.0000786.
[50] S. Jiang, Z. Wu, B. Zhang, H. Cha, Combined MvdXML and semantic technologies for green construction code checking, Appl. Sci. 9 (2019) 1463, https://doi.org/10.3390/app9071463.
[51] D.X. Zhang, J.Y. Zhang, J.N. Guo, H.M. Xiong, A semantic and social approach for real-time green building rating in BIM-based design, Sustainability 11 (2019) 16, https://doi.org/10.3390/su11143973.
[52] A. Pradhan, B. Akinci, C.T. Haas, Formalisms for query capture and data source identification to support data fusion for construction productivity monitoring, Autom. Constr. 20 (2011) 389–398, https://doi.org/10.1016/j.autcon.2010.11.009.
[53] R. Marroquin, J. Dubois, C. Nicolle, Ontology for a Panoptes building: exploiting contextual information and a smart camera network, Semantic Web 9 (2018) 803–828, https://doi.org/10.3233/SW-180298.
[54] M. Arslan, C. Cruz, D. Ginhac, Semantic trajectory insights for worker safety in dynamic environments, Autom. Constr. 106 (2019), 102854, https://doi.org/10.1016/j.autcon.2019.102854.
[55] M. Shahinmoghaddam, A. Nazari, M. Zandieh, CA-FCM: towards a formal representation of expert's causal judgements over construction project changes, Adv. Eng. Inf. 38 (2018) 620–638, https://doi.org/10.1016/j.aei.2018.09.006.
[56] R. Ren, J.S. Zhang, Semantic rule-based construction procedural information extraction to guide jobsite sensing and monitoring, J. Comput. Civil Eng. 35 (2021), https://doi.org/10.1061/(ASCE)CP.1943-5487.0000971.
[57] Y. Deng, J.C.P. Cheng, C. Anumba, Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison, Autom. Constr. 67 (2016) 1–21, https://doi.org/10.1016/j.autcon.2016.03.006.
[58] T.E. El-Diraby, H. Osman, A domain ontology for construction concepts in urban infrastructure products, (2011). https://doi.org/10.1016/j.autcon.2011.04.014.
[59] A. Sharafat, M.S. Khan, K. Latif, J. Seo, BIM-based tunnel information modeling framework for visualization, management, and simulation of drill-and-blast tunneling projects, J. Comput. Civil Eng. 35 (2021), https://doi.org/10.1061/(ASCE)CP.1943-5487.0000955.
[60] X. Xu, H.B. Cai, Domain ontology for utility infrastructure: coupling the semantics of CityGML utility network ADE and domain glossaries, J. Comput. Civil Eng. 35 (2021), https://doi.org/10.1061/(ASCE)CP.1943-5487.0000977.
[61] J. Zeb, An ontology of condition assessment technologies for sewer networks, Infrastr. Asset Manage. 7 (2020) 36–45, https://doi.org/10.1680/jinam.18.00034.
[62] J. Zeb, An eco asset ontology towards effective eco asset management, Built Environ. Project Asset Manage. 7 (2017) 388–399, https://doi.org/10.1108/BEPAM-11-2016-0061.
[63] J. Zeb, T. Froese, Transaction ontology in the domain of infrastructure management, Can. J. Civ. Eng. 39 (2012) 993–1004, https://doi.org/10.1139/l2012-054. IID–2.
[64] J. Zeb, T. Froese, D. Vanier, An ontology-supported asset information integrator system in infrastructure management, Built Environ. Project Asset Manage. 5 (2015) 380–397, https://doi.org/10.1108/bepam-02-2014-0012. IID-27.
[65] J.C. Dao, S.T. Ng, Y.F. Yang, S.H. Zhou, F.J. Xu, M. Skitmore, Semantic framework for interdependent infrastructure resilience decision support, Autom. Constr. 130 (2021), https://doi.org/10.1016/j.autcon.2021.103852.
[66] M. Murphy, E. Mcgovern, S. Pavia, Historic building information modelling (HBIM), Struct. Survey 27 (2009) 311–327, https://doi.org/10.1108/02630800910985108.
[67] X. Yang, Y.C. Lu, A. Murtiyoso, M. Koehl, P. Grussenmeyer, HBIM modeling from the surface mesh and its extended capability of knowledge representation, ISPRS Int J Geoinf. 8 (2019) 301, https://doi.org/10.3390/ijgi8070301.
[68] M. Previtali, R. Brumana, C. Stanga, F. Banfi, An ontology-based representation of vaulted system for HBIM, Appl. Sci. (Switzerland) 10 (2020) 1377, https://doi.org/10.3390/app10041377.
[69] P.C. Lee, W. Xie, T.P. Lo, D. Long, X. Tang, A cloud model-based knowledge mapping method for historic building maintenance based on building information modelling and ontology, KSCE J. Civ. Eng. 23 (2019) 3285–3296, https://doi.org/10.1007/s12205-019-2457-0.
[70] R. Quattrini, R. Pierdicca, C. Morbidoni, Knowledge-based data enrichment for HBIM: exploring high-quality models using the semantic-web, J. Cult. Herit. 28 (2017) 129–139, https://doi.org/10.1016/j.culher.2017.05.004.
[71] M. Bassier, M. Bonduel, J. Derdaele, M. Vergauwen, Processing existing building geometry for reuse as linked data, Autom. Constr. 115 (2020), 103180, https://doi.org/10.1016/j.autcon.2020.103180.
[72] P. Pauwels, D. Van Deursen, R. Verstraeten, J. De Roo, R. De Meyer, R. Van De Walle, J. Van Campenhout, A semantic rule checking environment for building performance checking, Autom. Constr. 20 (2011) 506–518, https://doi.org/10.1016/j.autcon.2010.11.017.
[73] D.A. Salama, N.M. El-Gohary, Automated compliance checking of construction operation plans using a deontology for the construction domain, J. Comput. Civil Eng. 27 (2013) 681–698, https://doi.org/10.1061/(asce)cp.1943-5487.0000298.
[74] P. Pauwels, T.M. de Farias, C. Zhang, A. Roxin, J. Beetz, J. De Roo, C. Nicolle, A performance benchmark over semantic rule checking approaches in construction industry, Adv. Eng. Inf. 33 (2017) 68–88, https://doi.org/10.1016/j.aei.2017.05.001.
[75] B. Zhong, C. Gan, H. Luo, X. Xing, Ontology-based framework for building environmental monitoring and compliance checking under BIM environment, Build. Environ. 141 (2018) 127–142, https://doi.org/10.1016/j.buildenv.2018.05.046.
[76] Y.C. Li, Q. Zhao, Y.H. Liu, X.H. Hei, Z.J. Li, Semiautomatic generation of code ontology using ifcOWL in compliance checking, Adv. Civil Eng. (2021) 2021, https://doi.org/10.1155/2021/8861625.
[77] B. Kamsu-Foguem, F.H. Abanda, M.B. Doumbouya, J.F. Tchouanguem, Graph-based ontology reasoning for formal verification of BREEAM rules, Cogn. Syst. Res. 55 (2019) 14–33, https://doi.org/10.1016/j.cogsys.2018.12.011.
[78] R.K. Soman, M. Molina-Solana, J.K. Whyte, Linked-Data based Constraint-Checking (LDCC) to support look-ahead planning in construction, Autom. Constr. 120 (2020), 103369, https://doi.org/10.1016/j.autcon.2020.103369.
[79] R.J. Scherer, S.E. Schapke, A distributed multi-model-based Management Information System for simulation and decision-making on construction projects, Adv. Eng. Inf. 25 (2011) 582–599, https://doi.org/10.1016/j.aei.2011.08.007.
[80] E. Curry, J. O'Donnell, E. Corry, S. Hasan, M. Keane, S. OÃ Â¢Ã Â Ã Â™Riain, Linking building data in the cloud: Integrating cross-domain building data using linked data, Adv. Eng. Inf. 27 (2013) 206–219, https://doi.org/10.1016/j.aei.2012.10.003.
[81] E. Corry, J. O'Donnell, E. Curry, D. Coakley, P. Pauwels, M. Keane, Using semantic web technologies to access soft AEC data, Adv. Eng. Inf. 28 (2014), https://doi.org/10.1016/j.aei.2014.05.002.
[82] H.-H. Wang, F. Boukamp, T. Elghamrawy, Ontology-based approach to context representation and reasoning for managing context-sensitive construction information, J. Comput. Civil Eng. 25 (2011) 331–346, https://doi.org/10.1061/(asce)cp.1943-5487.0000094.
[83] D. He, Z. Li, C. Wu, X. Ning, An e-commerce platform for industrialized construction procurement based on BIM and linked data, Sustainability (Switzerland) 10 (2018) 21, https://doi.org/10.3390/su10082613.
[84] M. Niknam, S. Karshenas, A shared ontology approach to semantic representation of BIM data, Autom. Constr. 80 (2017) 22–36, https://doi.org/10.1016/j.autcon.2017.03.013.
[85] S. Sobhkhiz, H. Taghaddos, M. Rezvani, A.M. Ramezanianpour, Utilization of semantic web technologies to improve BIM-LCA applications, Autom. Constr. 130 (2021), https://doi.org/10.1016/j.autcon.2021.103842.
[86] M. Park, K. won W. Lee, H. soo S. Lee, J.Y. Pan, J. Yu, P. Jiayi, J. Yu, Ontology-based construction knowledge retrieval system, KSCE J. Civ. Eng. 17 (2013) 1654–1663, https://doi.org/10.1007/s12205-013-1155-6. IID–1.
[87] J. Lee, Y. Jeong, User-centric knowledge representations based on ontology for AEC design collaboration, CAD Comput. Aided Design 44 (2012) 735–748, https://doi.org/10.1016/j.cad.2012.03.011.
[88] R. Costa, C. Lima, J. Sarraipa, R. Jardim-Gonçalves, Facilitating knowledge sharing and reuse in building and construction domain: an ontology-based approach, J. Intell. Manuf. 27 (2016) 263–282, https://doi.org/10.1007/s10845-013-0856-5.
[89] J. Zhang, T.E. El-Diraby, Social semantic approach to support communication in AEC, J. Comput. Civil Eng. 26 (2012) 90–104, https://doi.org/10.1061/(asce)cp.1943-5487.0000130.
[90] J. Beetz, J. Van Leeuwen, B. De Vries, IfcOWL: A case of transforming EXPRESS schemas into ontologies, artificial intelligence for engineering design, Pressure Vessels Piping 23 (2009) 89–101, https://doi.org/10.1017/S0890060409000122.
[91] P. Pauwels, W. Terkaj, EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology, Autom. Constr. 63 (2016) 100–133, https://doi.org/10.1016/j.autcon.2015.12.003.
[92] P. Pauwels, D. Van Deursen, J. de Roo, T. Van Ackere, R. de Meyer, R. Van de Walle, J. Van Campenhout, Three-dimensional information exchange over the semantic web for the domain of architecture, engineering, and construction, Artif. Intell. Eng. Design Anal. Manufact. AIEDAM 25 (2011) 317–332, https://doi.org/10.1017/S0890060411000199.
[93] M. Venugopal, C.M. Eastman, J. Teizer, An ontology-based analysis of the industry foundation class schema for building information model exchanges, Adv. Eng. Inf. 29 (2015) 940–957, https://doi.org/10.1016/j.aei.2015.09.006.

[94] C. Zhang, J. Beetz, B. De Vries, BimSPARQL: Domain-specific functional SPARQL extensions for querying RDF building data, Semantic Web 9 (2018) 829–855, https://doi.org/10.3233/SW-180297.

[95] M.H. Rasmussen, M. LefranÃ§ois, P. Pauwels, C.A. Hviid, J. KarlshÃ¸j, Managing interrelated project information in AEC knowledge graphs, Autom. Constr. 108 (2019), 102956, https://doi.org/10.1016/j.autcon.2019.102956.

[96] Y.C. Lee, C.M. Eastman, W. Solihin, An ontology-based approach for developing data exchange requirements and model views of building information modeling, Adv. Eng. Inf. 30 (2016) 354–367, https://doi.org/10.1016/j.aei.2016.04.008.

[97] E. E.-D.T, Domain ontology for construction knowledge, J. Constr. Eng. Manag. 139 (2013) 768–784, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000646.

[98] H.X. Liu, M. Lu, M. Al-Hussein, Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry, Adv. Eng. Inf. 30 (2016) 190–207, https://doi.org/10.1016/j.aei.2016.03.001.

[99] B.T. Zhong, C. Gan, H.B. Luo, X.J. Xing, Ontology-based framework for building environmental monitoring and compliance checking under BIM environment, Build. Environ. 141 (2018) 127–142, https://doi.org/10.1016/j.buildenv.2018.05.046. IID-.

[100] C. Zhang, J. Beetz, B. de Vries, BimSPARQL: Domain-specific functional SPARQL extensions for querying RDF building data, Semantic Web 9 (2018) 829–855, https://doi.org/10.3233/SW-180297.

[101] K. McGlinn, A. Wagner, P. Pauwels, P. Bonsma, P. Kelly, D. O'Sullivan, Interlinking geospatial and building geometry with existing and developing standards on the web, Autom. Constr. 103 (2019) 235–250, https://doi.org/10.1016/j.autcon.2018.12.026.

[102] B. Luiten, M. Böhms, A. O'Keeffe, S. van Nederveen, J. Bakker, L. Wikström, A hybrid linked data approach to support asset management, Crc Press-Balkema, Leiden, 2017, https://doi.org/10.1201/9781315375175-78.

[103] C. Boje, H. Li, Crowd simulation-based knowledge mining supporting building evacuation design, Adv. Eng. Inf. 37 (2018) 103–118, https://doi.org/10.1016/j.aei.2018.05.002.

[104] K. Janowicz, M.H. Rasmussen, M. Lefrançois, G.F. Schneider, P. Pauwels, BOT: The building topology ontology of the W3C linked building data group, Semantic Web 12 (2020) 143–161, https://doi.org/10.3233/SW-200385.

[105] M.H. Rasmussen, P. Pauwels, M. Lefrançois, G.F. Schneider, C.A. Hviid, J. Karshøj, Recent changes in the building topology ontology, in: 5th Linked Data in Architecture and Construction Workshop (LDAC 2017), 2017, https://doi.org/10.13140/RG.2.2.32365.28647.

[106] I. Esnaola-Gonzalez, J. Bermúdez, I. Fernandez, A. Arnaiz, Ontologies for observations and actuations in buildings: a survey, Semantic Web 11 (2020) 593–621, https://doi.org/10.3233/SW-200378.

[107] Y. Lu, Q.M. Li, Z.P. Zhou, Y.L. Deng, Ontology-based knowledge modeling for automated construction safety checking, Saf. Sci. 79 (2015) 11–18, https://doi.org/10.1016/j.ssci.2015.05.008. IID–1.

[108] S. Zhang, F. Boukamp, J. Teizer, Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA), Autom. Constr. 52 (2015) 29–41, https://doi.org/10.1016/j.autcon.2015.02.005.

[109] Linked Open Vocabularies, (n.d.).

[110] Y. Kalfoglou, M. Schorlemmer, Information-flow-based ontology mapping, in: OTM Confederated International Conferences" On the Move to Meaningful Internet Systems, Springer, 2002, pp. 1132–1151.

[111] M. Perin, L. Wouters, Using ontologies for solving cross-domain collaboration issues, IFAC Proc. 47 (2014) 7837–7842, https://doi.org/10.3182/20140824-6-ZA-1003.01575. Volumes.

[112] A. Cerezo-Narváez, A. Pastor-Fernández, M. Otero-Mateo, P. Ballesteros-Pérez, Integration of cost and work breakdown structures in the management of construction projects, Appl. Sci. 10 (2020) 1386.

[113] M. Compton, P. Barnaghi, L. Bermudez, R. García-Castro, O. Corcho, S. Cox, J. Graybeal, M. Hauswirth, C. Henson, A. Herzog, V. Huang, K. Janowicz, W. D. Kelsey, D.Le Phuoc, L. Lefort, M. Leggieri, H. Neuhaus, A. Nikolov, K. Page, A. Passant, A. Sheth, K. Taylor, The SSN ontology of the W3C semantic sensor network incubator group, Web Semant. 17 (2012) 25–32, https://doi.org/10.1016/j.websem.2012.05.003.

[114] F. Schütze, J. Stede, M. Blauert, K. Erdmann, EU taxonomy increasing transparency of sustainable investments, DIW Weekly Rep. 10 (2020) 485–492, https://doi.org/10.18723/diw_dwr:2020-51-1.