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A REVIEW OF THE APPLICATION OF ONTOLOGIES AND SEMANTIC WEB FOR BUILDING INFORMATION MODELLING AND DIGITAL TWINS BASED CONSTRUCTION MANAGEMENT

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SUMMARY*: As the construction industry is moving towards digitalisation, the integration of advanced technologies like Building Information Modelling (BIM) and digital twins has become essential for enhancing project efficiency. Currently, the industry has the capacity to operate at BIM Maturity stage 2 but faces challenges in achieving seamless data integration and interoperability. Progressing toward BIM Maturity Stage 3 could benefit from adopting semantic web and linked data technologies, which enable a more structured, machine-readable data environment. However, the path to this level of integration remains complex. At the heart of the semantic web lies ontologies, playing a pivotal role in structuring domain knowledge. Therefore, through a systematic literature review, this study explores the integration of ontologies and semantic web technologies in BIM or Digital Twin environments for construction management. This study provides a trend and theoretical analysis under different construction management use cases to identify how ontologies and semantic web technologies have been utilised during the construction execution phase. The study identified eight different use cases, including safety management, compliance checking, and construction planning and production control, among others. The findings emphasise that while there is great potential in using ontologies and the semantic web for data integration, significant barriers remain, such as data privacy concerns, scalability issues, and the complexity of ontology mapping. These findings underscore the importance of addressing these challenges to fully harness the capabilities of semantic web technologies within BIM environments, providing a potential roadmap toward realising BIM Maturity Stage 3 and to enhance collaboration and data exchange in the construction industry. This study provides a roadmap for future research and technological development in applying semantic web technologies to advance construction management.*

KEYWORDS*: Semantic Web, Ontologies, Linked Data, BIM, Digital Twins, Industry Foundation Classes (IFC), AEC Industry.*

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1. INTRODUCTION

The Architecture Engineering and Construction (AEC) sector is evolving towards cloud-based, scalable, and ubiquitous architecture to facilitate model generation, data exchange, and information intake (Venugopal et al., 2012). A typical construction project comprises multifaceted inputs from various streams such as materials, information, equipment, availability of space, labour, etc. (Schlenger et al., 2022). Different domains in the AEC industry store data in heterogeneous data formats, for example, BIM (XML or relational databases), cost estimations and project schedules in relational databases, material suppliers' product data in text, HTML or XML or relational formats (Niknam and Karshenas, 2017). In multi-data environments like construction projects, the data integration process and delivering a meaningful output from these data can be challenging (Schlenger et al., 2022). This is often referred to as the issue with interoperability within the construction industry (Niknam and Karshenas, 2017).

The concept of the semantic web allows various domains engaged in AEC projects to semantically represent building information on a specific entity in a manner that could be integrated with data from other domains (Niknam and Karshenas, 2017). The need to overcome interoperability issues, the desire for linking data across domains, and logical inference and proofs have fuelled the interest of AEC industry researchers to explore the application of semantic web technology for the AEC domain (Pauwels et al., 2017). Along with semantic web technologies, linked data technologies have the potential to create an open and collaborative environment for sharing, integrating, and linking data from many domains and data sources (Zhang and Beetz, 2016). The concept of the semantic web lies behind the linked data concept, which is the creation of a web of data with the help of data schemas, termed ontologies, that represent formal knowledge, concepts and their relationships within a domain (Schlachter, Rasmussen and Karlshøj, 2022). Furthermore, the application of ontologies and the semantic web within the AEC sector has progressively increased (Abanda et al., 2013; Pauwels et al., 2017; Farghaly et al., 2023).

Over the last decades, digital project models and model interchange formats have been the subject of study and standardisation, with the Industry Foundation Classes (IFC) schema at the heart of interoperability and supporting project stakeholder engagement (Laakso and Kiviniemi, 2012; Boje et al., 2020). The importance of advancing information management through semantic web technologies aligns with the maturity stages defined in the ISO 19650-1 document. As outlined in the standard, the progression from Stage 1 to Stage 3 reflects increasing integration, automation and collaboration. Stage 2 marks the transition to federated information models, forming the groundworks for more advanced digitisation such as web-scale, semantically enriched data exchange, anticipated within Stage 3. Currently, the concept of digital twins is also gaining more traction in the construction industry (Lu et al., 2019). The digital twin concept goes beyond the static modelling capabilities of BIM, which comprises BIM models, schedules, contracts, construction documents (submittals, change orders, RFIs, etc.), operational data collected by the embedded sensors, and data from AI and machine learning technology, etc. (Keen, 2021). Therefore, the availability of a well-defined data schema or structure is essential for the representation of complex information in a much more trustworthy and concise manner to apply the concept of Level 3 BIM and digital twins in the construction industry (Schlenger et al., 2022).

In the execution phase of a construction project, various stakeholders generate a large volume of data in diverse formats across multiple systems. This diversity presents significant challenges for data integration and makes it difficult to produce meaningful insights for decision-making. Thus, this paper focuses on exploring how semantic web technologies, especially ontologies, have been utilised for construction management use cases during the construction execution phase through a systematic literature review, specifically to support BIM/Digital Twin implementation. This paper primarily focuses on three objectives:

1. Review the extent to which semantic web technologies, linked data and ontologies have been applied in the BIM-based and Digital Twin-based construction management context and their related use cases during the construction execution phase.
2. Analysis of how semantic web tools have been utilised to cater the purposes of different use cases.
3. Identify current gaps and directions for future research.

Following the introduction, a brief literature review is presented to review the concepts of BIM, digital twin, semantic web, linked data, and ontologies, followed by a methodology chapter demonstrating the literature selection and analysis. The literature findings have been discussed under the identified use cases, accompanied by a brief trend analysis. Finally, an overview of the existing barriers and future research avenues relating to BIM and digital twin-based semantic web research is explored.

2. RESEARCH BACKGROUND

2.1 Building Information Modelling (BIM)

A sophisticated digital depiction of a built facility with significant information depth is called a building information model (Borrmann et al., 2018). However, a BIM model is not just the 3D representation of an asset; it is capable of expressing the semantics of a building model. One of the major goals of the concept of BIM is to achieve an open BIM, where vendor-neutral data formats are employed for seamless integration between different stakeholders representing a variety of disciplines. To address this issue, buildingSMART has developed an object-oriented data format termed Industry Foundation Classes (IFC), which offers prolific data structures that span practically all facets of constructed facilities (Pauwels et al., 2017).

The ISO 19650 series conceptualises information management maturity through three progressive stages. Stage 1 represents the conventional information management practice, which involves unstructured or structured data exchange through paper-based or digital means. Stage 2 (BIM according to ISO 19650 series) proposes the use of federated information models supported by a combination of manual and automated processes within a common data environment. Currently, Stage 2 BIM is being targeted to be applied within the construction industry, which involves local software platforms, file-based information interchange, and coordination settings (Pauwels and Petrova, 2020). The goal of Stage 3 maturity is to support more integrated and intelligent data environments through advanced information management technologies, moving beyond file-based approaches towards web-scale, object-based and data-driven platforms. However, a fileless and web-based building information platform is currently not completely supported by any technology (Pauwels and Petrova, 2020). This very idea of a web of Stage 3 maturity aligns closely with the principles of the Semantic Web, which advocates for machine-readable, interconnected data to enhance interoperability and cross-domain integration (Rasmussen et al., 2020).

2.2 Digital Twin

A digital twin is a digital portrayal of a physical asset that acts as a ‘living’ digital simulation model and is made possible by a large amount of data (e.g., operational data from bridges) and powerful data processing and interpretation procedures (Ye et al., 2019). The origin of the concept of digital twin traces back to Dr Michael Grieves’s presentation in 2002. Despite the lack of a widely accepted or agreed-upon definition for the term digital twin (Gerber et al., 2019), as per Tao et al. (2019), a digital twin comprises three major components: a physical artefact, a digital counterpart, and the connection which ties these two. This connection is referred to as the exchange of data, information, and knowledge between the physical and digital twin, which is powered by the advancements of sensing technologies such as computer vision, IoT devices, advanced analytics such as machine learning and high-speed networking (Rosen et al., 2015). Figure 1 illustrates the concept and artefacts of a digital twin.

Digital twins will enable the capturing of real-time data and communication with the stakeholders to optimise the decision-making process (Shirowzhan et al., 2020). Digital twins can be applied for different use cases such as facilities management and operation, asset condition monitoring, decision-making, simulations in design, and sustainable development (Brilakis et al., 2020). In addition, digital twins can be used to test what-if scenarios and novel techniques to simulate and make predictions regarding the asset (Taylor et al., 2019). Currently, the concept of digital twin in the construction industry is mostly applied during the operation phase of a building (Khajavi et al., 2019). To address this limitation, Sacks et al. (2020) have introduced the core concepts and workflow in implementing digital twins for the design and construction phases of buildings and infrastructure, coining it as Digital Twin Construction (DTC). As per Sacks et al. (2020), DTC is a data-driven construction management approach that uses continuous monitoring, data analytics, and proactive control systems to enhance situational awareness and decision-making throughout the design and construction phases. Despite the appealing nature of digital twins, there are numerous barriers to implementing digital twins in the construction industry. A construction project involves a strong collaboration between various stakeholders such as designers, consultants, contractors, suppliers, etc. (Ballard and Howell, 2003). These stakeholders produce information regarding the construction product and the process (Sacks et al., 2020). However, the information is produced using a wide array of digital tools with various data formats that are not interoperable with one another (Sacks et al., 2018). This issue can be referred to as the interoperability issue with the data (Schlenger et al., 2022). Semantic web technology and linked data are active research areas in the construction industry, offering tools that facilitate improved data integration, exchange and interoperability (Pauwels et al., 2017). While these technologies do not inherently solve the interoperability challenges, they provide a framework that can support more seamless data sharing when accompanied by standardised practice.

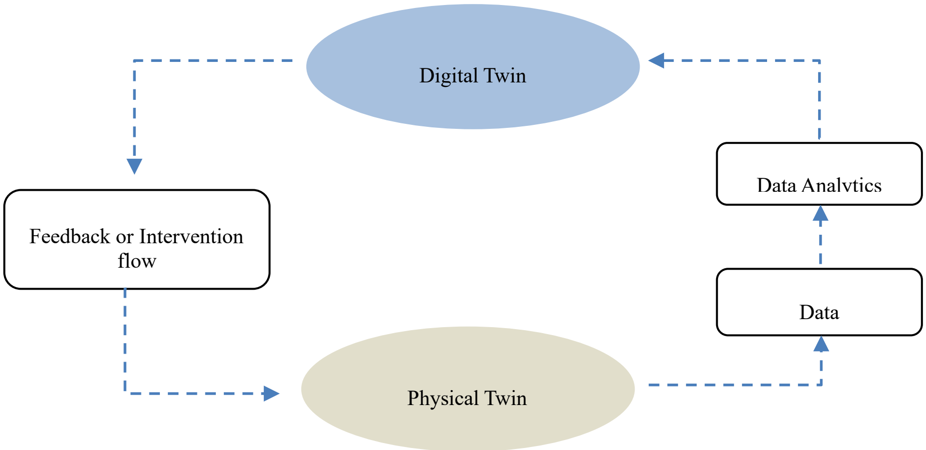

Figure 1: Concept of digital twins.

2.3 Semantic Web

In the early 2000s, Tim Berners-Lee (2009) presented the concept of the semantic web, with Linked Data as a subset. The semantic web is often termed as the 'Web 3.0', which is the Web of connected or linked data; whereas Web 1.0 is the Web of documents and Web 2.0 is the Web of application silos (Nath et al., 2014). The concept of the semantic web can be considered an extension of the concept of the World Wide Web, which is the Web of documents, to the Web of data (Niknam and Karshenas, 2017). It expands the network of hyperlinked human-readable web pages by introducing machine-readable metadata regarding pages and the way they are related to one another, allowing automated agents to browse the Web with greater intelligence and execute activities on behalf of users (Berners-Lee, 2009). Semantic web technologies allow individuals to establish Web-based data repositories, develop vocabularies, and design data-handling rules. There is a well-established set of standards and functionalities, such as Web Ontology Language (OWL), Shapes Constraint Language (SHACL), SPARQL, etc., which accommodate knowledge inference, reasoning, rule checking, and data querying (Schlenger et al., 2022).

Semantic web stack is deployed to illustrate the technical standards that enable Linked Data and the Semantic Web, which can be found in Borrmann et al. (2018). Lower levels of this stack display commonly used technology such as Uniform Resource Indicators (URIs), Unicode, and Extensible Markup Language (XML), which are utilised in World Wide Web hypertext. Furthermore, the core consists of the Resource Description Framework (RDF) and the schema for modelling vocabularies for taxonomies (RDFS), ontologies (OWL), and rules [Rule Interchange Format (RIF), Semantic Web Rule Language (SWRL)], as well as the query language SPARQL. They serve as the foundation for more intellectual levels centred on Logic, Proof, and Trust.

In a semantic web environment, a variety of semantic domains can be expressed and merged using directed labelled graphs (Pauwels and Terkaj, 2016), where each node within a graph indicates an actual concept or object, and each labelled arc indicates the logical relationship among such concepts or objects. RDF can be used to generate these graphs (Schreiber and Raimond, 2014). RDF triple is used to represent statements in any model as a triple that includes a subject, a predicate, and an object (W3C, 2014). Formal ontologies are used in the semantic web to define the concepts (classes) and the relationships between concepts. Ontologies are utilised to build domain knowledge bases (Gruber, 1993). A domain knowledge base is a repository for gathering, arranging, and distributing information (Niknam and Karshenas, 2017).

2.4 Ontologies

Dictionaries, classifications, and ontologies play a vital role in facilitating concise definitions and data interchange (Borrmann et al., 2018). Ontologies can be defined as “an explicit specification of a conceptualisation” (Neches et al., 1991). An ontology defines basic terms and relationships of a certain domain knowledge consisting of vocabularies to express terms and a set of rules to combine the terms with their relationships (Farghaly et al., 2021). An ontology provides three major benefits in the field of knowledge modelling and management (Ding et al., 2016): 1.) it enhances model extendibility and flexibility, 2.) enables a robust semantic interpretation, and 3.) improves retrieval of knowledge by enhancing the concept-level retrieval requests.

The linked data approach is often considered the widely used approach in publishing ontologies by construction researchers (Curry et al., 2013; Farghaly, 2019). Different terms necessary to interpret knowledge are modelled as concepts using ontologies, and through statements, these concepts are linked to their properties (Farghaly et al., 2022). These statements are represented using RDF triples/semantic triples: a subject, a predicate, and an object (W3C, 2014).

Multiple statements are merged by utilising the logical operators in an ontology published via Linked Data (Farghaly et al., 2022). RDF triples are the individual statements that make up the resultant graph, known as an RDF graph (Pauwels et al., 2017). The semantic structure can be enhanced using the Web Ontology Language (OWL), which can be utilised to create complex RDF statements (Farghaly et al., 2022). This strategy makes it possible to infer new knowledge through reasoning and revealing implicit relationships, allowing different systems to interpret and integrate data more consistently, thereby enhancing semantic interoperability (El-Diraby et al., 2005).

2.5 Construction Industry and Semantic Web

The Semantic Web standards could lay a solid basis for interoperability in the BIM and digital twin environments, necessitating integrated data (Schlenger et al., 2022). The utilisation of ontologies enhances data to be both machine-readable and machine-interpretable, facilitating a seamless exchange of information. The concept of the semantic web allows various domains engaged in AEC projects to semantically represent building information on a specific entity in a manner that could be integrated with data from disparate domains (Niknam and Karshenas, 2017).

The need for semantic web technologies has been addressed in the BIM Maturity Stages; where BIM Maturity Stage 3 emphasises processes and information to be transferred on a web-scale and fully integrated across disciplines and enterprises (Niknam and Karshenas, 2017). Information is transmitted on the Web utilising open standards for BIM Maturity Stage 3, and interoperable and decentralised model servers enable collaborative work on interoperable models and structured data. Therefore, in order to achieve this ultimate goal of BIM Maturity Stage 3, the same path of moving forward from the Web of documents to the Web of data, which is the semantic web, must be followed (Bizer et al., 2009; Lee and Kim, 2011).

Over the last decade, digital modelling and model exchange formats have been the focal point for research and standardisation, with IFC schema playing a central role in enhancing interoperability (Laakso and Kiviniemi, 2012; Boje et al., 2020). Initially, the IFC schema was only available in the STEP EXPRESS and Step Physical File formats, hindering the deployment of linked data technologies, and leaving the data within the construction domain isolated within information silos (Pauwels et al, 2018). Efforts by researchers (Beetz, van Leeuwen and de Vries, 2008) and (Pauwels and Terikaj, 2016), however, have pioneered the transformation of the IFC schema to the ifcOWL ontology format. Nonetheless, the complex structure of the ifcOWL ontology impedes efficient reasoning, and its large size limits its extensibility and modularity (Rasmussen et al., 2020). In response, the W3C Community Group on Linked Building Data (LBD) has undertaken several projects to develop simpler, more modular, and extensible ontologies. To date, the LBD group has introduced several streamlined ontologies such as the Building Topology Ontology (BOT), Product Ontology (PRODUCT), Properties Ontology (PROPS), and Geometry Ontology (GEOM), which encompass concepts from the IFC dataset. These ontologies provide a foundational framework for describing buildings, prompting industry stakeholders to develop these ontologies further or to create new ones (Schlachter, Rasmussen and Karlshoj, 2022).

Moreover, authors such as El-Diraby, Lima and Feis (2005) and Staub-French et al. (2003) have taken early initiatives to incorporate ontologies into construction knowledge management. Apart from the building topology, knowledge management and ifcOWL; many other researchers have developed various ontologies and ontology-based solutions to perform various construction industry use cases. Furthermore, there are studies focusing on different stages of construction. Considering the pre-construction stage, studies such as; Boger et al. (2018) on automatic generation of product proposals, Nepal et al. (2009) on querying design conditions and during the post-construction stage or facilities management and operation stage studies such as; Corry et al. (2015) on environmental and energy management of buildings, Brick ontology on providing a semantic metadata standard for building assets and relationships (Lee et al., 2023), SAREF ontology (especially the SAREF4BLDG extension) on smart appliances (Castro et al., 2023) etc. When considering the extant literature, it is evident that most ontology research is being conducted focusing on the post-construction stage such as studies on energy management (Pruvost, Wilde and Enge-Rosenblatt; 2023; Li and Hong; 2022), smart buildings (Chamari, Petrova and Pauwels; 2023; Kumar and Mani, 2022). However, there is a considerable gap in research on the application of semantic web technologies during the construction stage, where there are a multitude of tasks to be carried out.

Despite the recognised importance of semantic web technologies in advancing BIM and digital twin applications and the many initiatives made by researchers, there is a notable gap in the literature regarding systematic reviews on their application within the construction sector, especially in the construction management domain during the construction execution phase and in the incorporation of BIM and digital twin concepts. Effective construction management tasks require access to vast amounts of data from different data sources in heterogeneous formats, leading to interoperability issues. Thus, ontologies and semantic web technologies can be utilised to overcome this barrier. Moreover, another compelling reason is the unavailability of a central repository to search and retrieve data about available ontologies within the construction domain, making researchers create new ontologies for the same use case and causing redundancies. This deviates from the W3C best practice guideline on reusing existing ontologies and vocabularies to enhance interoperability and reduce redundancies. Thus, this study attempts to bridge this gap by exploring the application of semantic web technologies and ontologies within the construction management domain, particularly within the context of BIM and digital twin. This study attempts to document ontologies and perform a technical analysis within the construction management domain, thus preventing redundancies in ontology design and paving the way for new developments in ontology engineering.

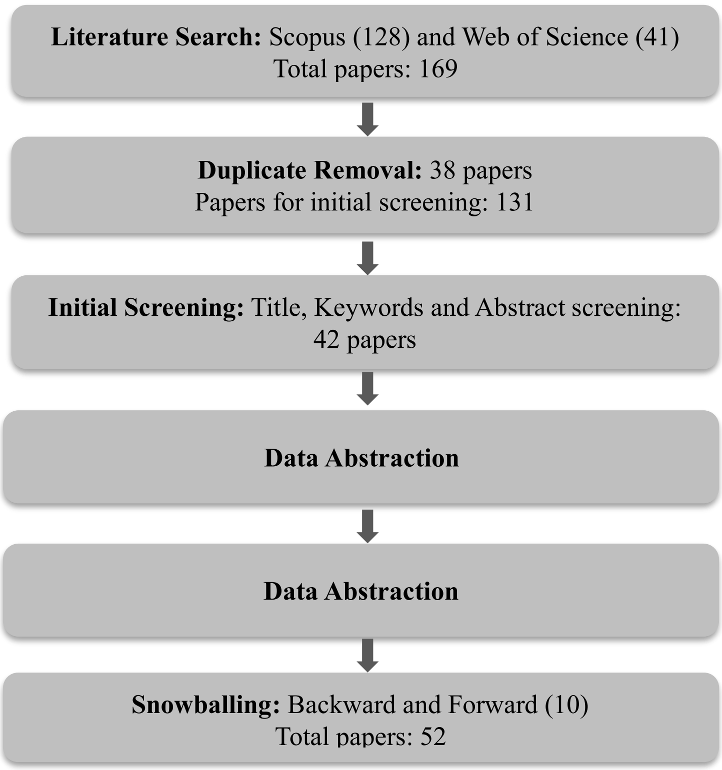

Figure 2: Research Process.

3. METHODOLOGY

This study adopts a systematic literature review approach to identify the extent to which semantic web technology and ontologies have been applied in BIM and Digital Twins paradigms in the construction industry during the construction execution phase. The study seeks to address the following key questions;

1. What are the emerging trends associated with integrating semantic web technologies, ontologies and linked data with BIM and digital twin concepts in the realm of construction management?
2. What are the different use cases where semantic web technologies have been utilised for construction management within BIM or digital twin settings?
3. What gaps or limitations are evident in the current body of research on this topic?
4. What directions should future research take to further develop and leverage semantic web technologies in construction management in BIM or digital twin settings?

The study was conducted by systematically screening articles extracted from previous publications. The study follows a similar approach as Snyder (2019) and Ekanayake et al. (2021), which provides a systematic process to identify, evaluate and synthesise relevant literature. The study encompasses three major stages: literature search, selection, and data abstraction (Ekanayake et al., 2021). The research process is illustrated in Figure 2.

3.1 Literature Search and Initial Screening

To ensure a comprehensive literature review and mitigate the limitations associated with relying on a single database, relevant publications for the selected topic were extracted from two databases, namely, Scopus and Web of Science. Advanced search tools were deployed to search for relevant journal papers, conference proceedings, industry reports, scholarly reports, technical reports and other forms of publications based on their title, abstract and keywords. Four sets of keywords were used, reflecting the construction industry, BIM and digital twin paradigm, semantic web paradigm and construction management paradigm. The keywords adopted were;

“(TITLE-ABS-KEY ("construction industry" OR "built environment" OR "construction project" OR "AEC industry") AND (BIM OR "building information modelling" OR "digital twin" OR "Building Information Modeling") AND ("semantic web" OR ontology OR "linked data" OR "Knowledge graph") AND (manage* OR plan* OR control*))”

The Scopus database delivered 128 results, while the Web of Science database provided 41 results, and among them, 38 duplicates were removed, making a total of 131 studies for initial screening. During the initial title, keyword and abstract screening process, 79 studies were deemed irrelevant. The exclusion criteria were as follows;

- This study focuses only on the construction execution phase; thus, studies related to pre-construction and post-construction operation and maintenance phases were disregarded.
- Was not focusing on building construction domain; studies focusing on infrastructure projects were excluded.
- Was not incorporating BIM or digital twin concepts
- Was a literature review study without proposing an ontology-based framework or case study to fulfil construction management use cases.
- Only the studies written in the English language were considered

Thus, 42 studies were brought forward for the full-text screening stage. Furthermore, 10 more papers were added through snowballing, making a total of 52 papers to be reviewed spanning from the year 2005 to 2023. Moreover, it should be noted that the literature search for this study was conducted in April 2023.

3.2 Data Abstraction

Upon selecting the final sample of articles, a proper method of data abstraction should be decided. According to Snyder (2019) data abstraction can mainly take two forms; 1.) summarising information in the form of descriptive information, such as title, authors, year of publication, affiliation, source of publication, key emphasis and findings, 2.) data abstraction in the form of conceptualisation of ideas in a theoretical perspective. However, the selection of the data abstraction method mainly depends on the objectives of the study. As mentioned previously, the main objectives of the study is to present a holistic overview of the trends, use cases (how semantic web tools are incorporated to deliver the use cases), limitations and future research direction related to the integration of semantic web technologies, specially ontologies for BIM-based or digital twin-based construction management during the construction execution phase of building construction projects. Furthermore, it should be highlighted that this study does not attempt to synthesise a conceptual or theoretical framework. Consequently, the first data abstraction approach was utilised to extract relevant information from the selected set of articles to arrange and comprehend the common themes and patterns among the studies covered in those publications.

The analysis conducted in this study is structured into two primary sections: trend analysis and theoretical analysis.
1. Trend analysis: This section provides an overview of the distribution of publications based on the year of publication and applied use cases.
2. Theoretical analysis: This component consists of two sections, focusing on the categorisation of ontologies into core and domain ontologies.

- High level ontologies: This section represents high-level and central ontologies pertaining to the construction management domain. These ontologies provide essential, high level representations of construction-related concepts. These ontologies can be utilised as foundational structures when developing domain-specific ontologies to support various construction management tasks. It should be highlighted that these ontologies do not demonstrate the same level of abstract nature as upper-level ontologies such as UFO or DOLCE.
- Domain ontologies: These ontologies focus on a specific area of knowledge. This subsection aims at evaluating domain ontologies based on semantic web technologies employed to support each considered construction management use case.

4. ANALYSIS OF THE FINDINGS

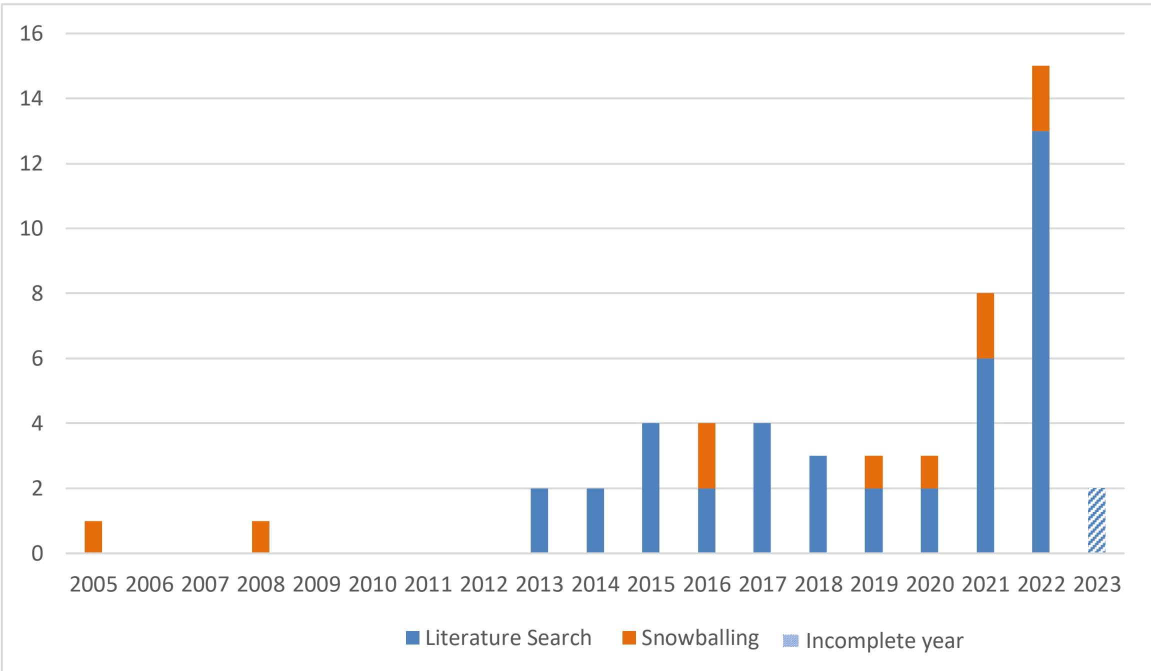

Figure 3: Distribution of reviewed papers by the year of publication.

4.1 Trend Analysis

This section provides a statistical overview of the selected 52 papers. Among the selected set of papers, there were 30 journal articles across 15 journals, among which the majority of 9 papers were published on the Automation in

Construction journal and four papers in the Advanced Engineering Informatics. Moreover, 21 conference papers were found distributed over 12 conferences, among which the International Conference on Computing in Civil and Building Engineering, the International Symposium on Automation and Robotics in Construction, the Linked Data in Architecture and Construction Workshop and the European Council on Computing in Construction recorded 3 papers each. Moreover, one chapter was also included in the selected set of papers. The following sub-sections provide a statistical perspective on the reviewed papers in terms of publication date and the applied use cases.

4.1.1 Distribution by Publication Date

Figure 3 illustrates the distribution of the 52 research articles according to the year of publication. Among the selected set of papers, the year of publication ranges from 2013 to 2023. The two studies recorded during 2005 and 2008 were extracted through a backwards snowballing approach. Moreover, it can be noticed that there is a growing trend in conducting research on the semantic web and ontologies, and it peaked in 2022, given that this study was conducted during the early half of 2023.

4.1.2 Distribution by Applied Use Cases

This section provides an in-depth review of the semantic web and ontology use cases in BIM and digital twin paradigms. Figure 4 illustrates the various use cases discussed within the selected set of literature. Utilisation of semantic web technologies and ontologies to achieve these use cases is discussed in the following chapter.

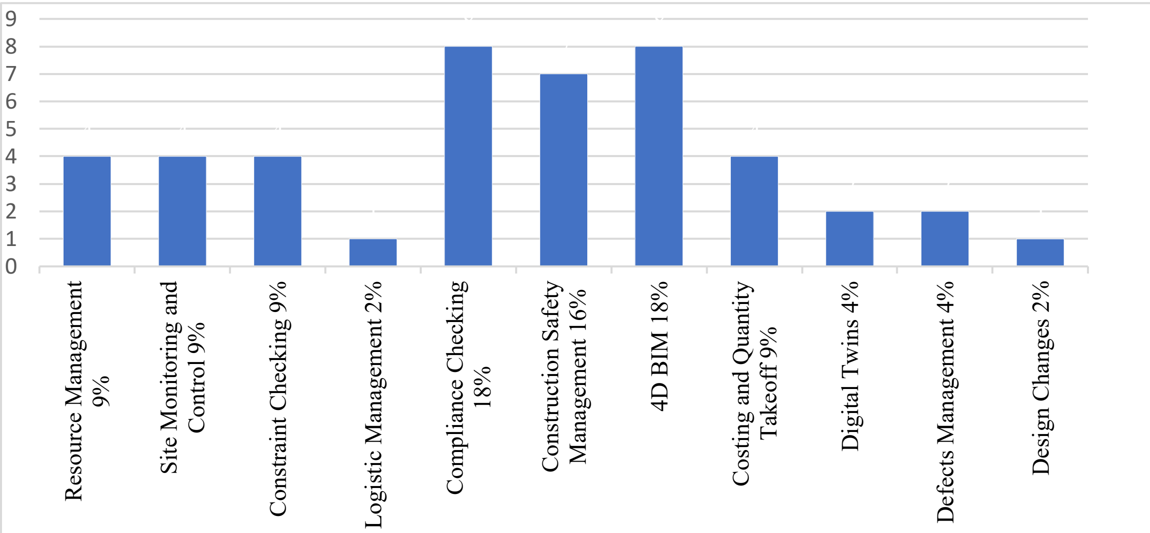

Figure 4: Distribution of studies based on applied use cases.

4.2 Theoretical Analysis – High Level Ontologies

This section of presents high level ontologies comprising a high level of formalisation and conceptualisation that can be extended with domain ontologies that can be used to implement various construction management related use cases.

4.2.1 ifcOWL

IFC is the data schema and file exchange format developed by BuildingSMART for BIM model data (Pauwels and Terkaj, 2016). IFC schema is represented in EXPRESS Language. Early initiatives to convert the IFC schema to OWL format were first proposed by Beetz et al. (2005, 2008). Building upon this foundational work, Pauwels and Terkaj (2016) executed a direct mapping of the EXPRESS schema to OWL, producing the ifcOWL ontology. They also introduced a tool to convert the IFC EXPRESS schema to ifcOWL in an OWL2 DL ontology. The ifcOWL ontology is fully backwards compatible with the IFC EXPRESS schema. IfcOWL includes classes for fairly fine-grained categorisations in terms of semantic information. However, the ifcOWL ontology comprises two main limitations: 1.) complicated structure providing implications such as inefficiency in the reasoning process, and poses challenges for users in understanding and navigating the ontology, 2.) large size hampering its extensibility and modularity (Rasmussen et al., 2020).

4.2.2 BOT

Building Ontology Topology (BOT) is a lightweight ontology developed by the Linked Building Data (LBD) Community Group of the World Wide Web Consortium (W3C) to overcome the size and complexity concerns in the ifcOWL ontology. It provides a high-level demonstration of the building topology, which focuses on spaces and storeys, building elements and their subcomponents, geometry and the way those are related to one another (Rasmussen et al., 2020). BOT includes three main classes: Zone, Element, and Interface. BOT ontology demonstrates alignments mainly to ifcOWL and DOLCE Ultralite Ontologies. In addition to the BOT ontology, the LBD has developed several other lightweight ontologies, such as product ontology (PRODUCT), properties ontology (PROP), geometry ontology (GEOM), etc.

4.2.3 DiCon – Digital Construction Ontology

DiCon is a suite of ontologies aiming to provide a higher-level representation of modelling construction workflow by integrating data residing in various systems and sources (Zheng et al., 2021). The novelty of the ontology suite resides within the attempt at integrating heterogeneous and multi-context information, especially taking into consideration various ICT platforms. DiCon comprises of six ontology modules namely, Entities, Process, Information, Agents, Variables, and Context. Furthermore, alignments were made with ifcOWL, BOT, SSN/SOSA, SAREF, PROV-O, OWL-Time ontology, QUDT and BFS ontologies. Due to the high level nature of the ontology suite, detailed classification hierarchies on domain entities are absent; thus, when reusing for different use cases, the ontology needs to be extended.

4.2.4 BIMSO and BIMDO

Niknam and Karshenas (2016, 2017) developed two ontologies to represent building topology called BIM Shared Ontology (BIMSO) and BIM Design Ontology (BIMDO). The BIMSO ontology was developed with the intention of sharing and exchanging building information between various domains in the construction industry. The ontology employs RDF/OWL languages, and it comprises only a few classes and connections aimed at defining the elements, levels, spaces, and development phases of a structure, and it depends on the entire Uniformat II categorisation system to further organise the elements. Moreover, the BIMDO ontology offers the essential object attributes to represent relationships between elements, zone subdivisions, and quantification of these interactions. Nevertheless, the major limitation of ontology is that it is not publicly available for access.

4.2.5 TUBES System Ontology (TSO)

The TUBES System Ontology (TSO) by Pauen et al. (2021) focused on outlining the topology of the interconnected building services systems and integrating it with the building spatial structure. Version v0.2 of the ontology consists of 24 classes, 69 object properties and 1 data property and is expected to expand in the future. The TSO ontology covers several concepts: core terminologies (zone, system and state), hierarchy, structure, functions, sources and sinks, and linking systems and zones. Furthermore, the proposed ontology can be aligned to BOT, ifcOWL and SAREF ontologies.

4.3 Theoretical Analysis – Domain Ontologies for BIM-Based Construction Management

This section of the study provides a comprehensive analysis of the different use cases of ontologies and semantic web tools integrated with the BIM or Digital Twin domain. The analysis provides an understanding of how semantic web tools have been utilised to achieve the applied use cases by identifying;

- The domain and subdomain focused on the study
- The knowledge acquisition methods
- Ontology development platform used
- Inferencing tools used
- Query languages utilised
- Ontology validation method
- Mapped ontologies

Furthermore, further details, such as inputs and outputs of the proposed solutions, are discussed depending on the use case.

4.3.1 Construction Safety Management

This sub-section provides an analysis of the ontologies identified related to different use cases of safety management. Table 1 provides a brief overview of the technical tools utilised in the ontologies developed for construction safety.

Table 1: Ontologies related to construction safety.

Ref	Ontology	Area Focused	Knowledge Acquisition	Rule Interpretation	Ontology Development	Querying	Ontology Validation	Mapped Ontologies
A	Construction Safety Ontology	Safety management	Occupational Safety and Health Administration (OSHA) regulation 1926 (OSHA 2013), Occupational Injury and Illness Classification Manual (BLS 1992)	SWRL rules in Jess rule engine	Protégé	NA	Consistency checking: Pellet reasoner, expert opinion, and using a BIM-based job hazard analysis application	NA
B	SafeConDM	Fall from hazard	Case study BG Bau 100 regulation	Answer Set Programming (ASP) rules	Protégé	NA	Case study	Construction Safety Ontology ifcOWL
C	Safety and Health Exchange (SHE)	Design for Safety (DfS)	Press releases Investigation reports Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR)	NA	Protégé	SPARQL	Consistency checking: Hermit reasoner	ifcOWL
D	Construction Safety Management Ontology	Safety rule checking	Chinese safety standards	SWRL	Protégé	NLP-based query system	Case study	NA
E	SafeCon	Prevention through Design (PfD)	Safety regulations Domain experts	NA	Protégé	NA	Domain experts, Software development, benchmarking	Construction Safety Ontology, SafeConDM, ifcOWL

A: Zhang et al. (2014 ; 2015), **B**: Li et al. (2020 ;2022) **C**: Farghaly et al. (2022), **D**: Shen et al. (2022), **E**: Johansen et al. (2023)

Zhang, Boukamp, and Teizer (2014, 2015) developed a construction safety ontology to formalise safety management knowledge. The ontology consists of three main domain ontology models, namely, the Construction Product Model (contains details about building elements and acts as the primary interface for BIM integration), Construction Process Model, and Construction Safety Model. Furthermore, the authors have explored the interaction between the proposed ontology and BIM. The ontology employs SWRL rules to create a safety regulation rule base. Moreover, a prototype application of ontology-based work hazard analysis and 4D visualisation is implemented to demonstrate the applicability and effectiveness of the created ontology. However, this prototype application cannot detect safety issues associated with construction site layout. Moreover, the inability to update the BIM model frequently reflecting site conditions, limits the results generated through this application.

The study conducted by Shen et al. (2022) proposed an automatic safety risk detection and prevention system for a construction process by using an ontology-based SWRL safety rule library with Natural Language Processing (NLP) by incorporating 4D BIM. For this purpose, the authors have developed a Construction Safety Ontology, which incorporates important knowledge of the construction process, various forms of safety accident knowledge linked to the construction process, and existing knowledge and relevant safety solutions. The safety risks were identified by linking the 4D BIM model with the developed ontology containing SWRL safety rules. NLP was deployed to present the identified results intelligently.

SafeConDM ontology proposed by Li et al. (2022) incorporates BIM models to reason construction safety compliances and to devise mitigation measures. The currently developed version of the study mainly focuses on fall from height hazards. The authors plan to extend the current version to vehicle strike hazards, electrocution, and vehicular blind spots in the future. Farghaly et al. (2022) developed the Safety and Health Exchange (SHE) ontology as a part of the project Discovering Safety Programme, which intends to create new knowledge for the prevention of accidents in the future by creating a new approach for data analysis and aggregating data from different sources worldwide. The primary purpose of the SHE ontology is to identify and manage safety risks during the design and planning stage by reviewing various construction accident reports recorded within the UK. Moreover, the authors mapped the SHE ontology with ifcOWL using an automated ontology management tool called Alignment-Maker, imposing a matching threshold of 75%. Secondly, a manual matching process was conducted to check the semantics and syntactic of the matches produced by the Alignment-Maker.

Most of the ontology-based safety management studies consider construction projects as a static model, neglecting the temporal effects, where only the safety hazards related to a single element are queried without considering the impact of other elements when the schedule progresses. Thus, to fill this gap, Johansen, Schultz and Teizer (2023) proposed a 4D BIM-based benchmark model and construction safety ontology, which covers falls from height and struck-by falling object hazards by incorporating the schedule to demonstrate the impact of spatiotemporal dynamics. The proposed ontology was validated using a benchmark BIM model, and multiple schedules were generated through a scheduler programme developed through a rule-based approach, considering geometry and topological relationships. A case study was conducted using the SafeConAI platform, utilising the developed ontology.

One of the key observations related to Table 1 is that the Construction Safety Ontology developed by Zhang et al. (2014; 2015) has mapped SafeConDM (Li et al., 2020; 2022) and SafeCon (Johansen et al., 2023) ontologies, which is a positive tendency considering one of the main fundamentals behind semantic web is to reuse existing ontologies than to make new ontology for each use case. Moreover, the majority of the listed ontologies focus solely on the fall from hazard risk events and often overlook the spatio-temporal effects. Furthermore, it can be seen that several ontologies have been developed for the same purpose; this could be due to the unavailability of published ontologies. Another reason could be that the ontologies are developed to comply with different safety standards. However, core structure and some high-level concepts in one ontology might be reused to create another; still, significant work needs to be carried out to ensure that the new ontology complies with the standards it follows.

4.3.2 4D BIM

This section deals with the ontologies related to 4D BIM schedule generation and other related use cases. Among the identified studies, Wu and Ma (2022), Wang and Song (2015), and Doukari et al. (2022) focused on deploying an ontology-based approach for automated schedule generation. Table 2 provides an overview of technologies utilised in generating schedules.

Wu and Ma (2022) proposed a multi-phase framework for automatic construction schedule generation through 1.) data extraction from the BIM model, 2.) data processing using an ontology system demonstrating constraint rules, 3.) schedule generation using genetic algorithms, and 4.) schedule evaluation. Wang and Song (2015) proposed a construction schedule generating approach, where the IFC file of the BIM model and ontology knowledge base on regulations and experience on construction progress schedule is used to generate a construction matrix (MoCC). Through a genetic algorithm, the created MoCC matrix generates a construction schedule.

The study conducted by Doukari et al. (2022) proposed a 'Renovation 4D Planning Ontology' as a part of the RINNO project. The developed ontology acts as the data layer for the RINNO Renovation Engine, a digital tool developed as a part of the study. The ontology consists of nine classes, and the 'Renovation Activity' class covers a wide range of renovation scenarios. Furthermore, the ontology has been populated into a database consisting of multiple tables using SQL Server, each representing a concept of the ontology. However, extensive details regarding the proposed ontology have not been provided in the publication.

Table 2: Ontologies related to 4D BIM schedule generation.

Ref	Ontology	Knowledge Acquisition	Rule Interpretation	Ontology Development	BIM Data Extraction	Schedule Generation	Ontology Validation
Schedule Generation							
A	NA	NA	Logic rules	Protégé	Revit using Visual Studio	Genetic Algorithm (MoCC)	Case Study
B	Renovation 4D Planning Ontology	NA	NA	Protégé	Revit and Synchro Pro	RINNO Renovation Engine	Case Study
C	Details not available						

A: Wu and Ma (2022), **B**: Doukari et al. (2022), **C**: Wang and Song (2015)

Even though all three studies above have managed to generate 4D schedules automatically, the impact on schedule generation through multiple constraints related to construction projects has been overlooked.

Table 3 illustrates ontology-based approaches for 4D BIM use cases.

Table 3: Ontologies related to 4D BIM use cases.

Ref	Ontology	Area Focused	Knowledge Acquisition	Rule Interpretation	Ontology Development	Querying	Ontology Validation	Mapped Ontologies
4D BIM Use Cases								
A	Relationship Ontology	Construction sequencing	Sequencing knowledge from previous research	NA	NA	NA	Survey	ifcOWL
B	Claim4D-Onto	Delay claims	Articles Textbooks Legal documentation Past experience	NA	Protégé	NA	Technical validation: consistency checking, Survey, Case study	NA
C	4DCollab Ontology	4D synchronous collaboration sessions	Rigorous experiment-focused approach	NA	Protégé	SPARQL	NA (Prototype under-development)	ifcOWL

A: Han et al. (2015), **B**: Guevremont and Hammad (2021), **C**: Boje et al. (2019, 2021, 2022)

Han et al. (2015) proposed an ontological approach for the interpretation of construction sequencing rationale for visual-based progress monitoring under low visibility scenarios using a low-Level of Detail (LoD) 4D BIM model. The proposed ontology provides a platform for querying geometric and connection information from the BIM model. In the proposed ontology, four main classes have been incorporated to show the physical relationships between building elements, namely, connected to (attached to, supported by), embedded in (structural, non-structural), enclosed by, and covered by. With the reasoning mechanism incorporated with BIM, the progress status of visually undetectable building elements is determined. The authors conducted a case study to determine the progress and validated the ontology and the classification mechanism through a Charrette test. In the proposed approach, the progress determination solely depends on photographs. However, the sufficiency of photographs to measure progress, the inability to determine aspects of construction quality, and the inability to determine liability and acceptance of those liabilities are several limitations of the study.

As a part of the 4Dcollab project, Boje et al. (2019), Boje et al. (2021), and Boje et al. (2022) have proposed a 4D Collab prototype, which assists in Synchronous Collaboration Session (SCS) for decision-making with 4D BIM-based planning through a user-centric method. The developed framework includes several components, namely, a client application layer, a server application layer, a BIM data layer and a Semantic Web layer. A 4D Collab Ontology has been developed for the semantic web layer. 4D Collab ontology is aligned with IFC4, and the proposed approach consists of several limitations regarding formalising user-model relationships, data availability and accessibility, data security and efficiency in traversing the graph model. Thus, the proposed ontology is being iterated for further enhancements. Guévremont and Hammad (2021) proposed a multi-disciplinary ontology that uses visual analytics to link delay claims with 4D simulation. This blend allows the delay effects and causes, and responsibility to be portrayed and analysed in a 4D simulation, which could potentially be employed in delay claims management and prevention.

Even though a considerable amount of research is being done on the 4D BIM avenue, there are still more areas to cover, such as site analysis, spatial conflict detection, workspace congestion avoidance, etc.

4.3.3 Compliance Checking

Among the selected literature, many studies were focused on developing ontologies on compliance checking in the BIM environment. This study identified numerous ontology-based applications in various areas related to compliance checking, such as building accessibility, fire regulations, etc. Table 4 provides an overview of the studies related to compliance checking.

The study by Shi and Roman (2017) developed a technique for extracting building accessibility regulation documents and then transforming them into executable rules for semi-automatic compliance testing of BIM models. In their case study, the authors used regulatory texts from Chapter 13.2 of ISO 21542:2011 (accessibility requirements of stairs and their components) for semantic annotation to enrich the domain ontology. The annotation results were used to create SWRL rules manually. The enriched domain ontology is mapped against the IFC schema so that the created SWRL rules can be transformed into executable BIM rules. Beach and Rezgui (2018) developed a proof-of-concept user interface by encoding building regulations, aligning BIM standards to regulations, and finally to execute regulations and generate human readable regulation document. Similarly, many authors such as Bus et al. (2018) focused on French smart building code to develop a modelling charter to standardise the building data modelling and sharing process using semantic web technologies to align BIM models with the regulatory requirements, Jiang, Shi and Wang (2022), automated code compliance checking using BIM and rule-based reasoning, Zheng et al. (2022) knowledge-informed framework for improved automated rule checking based on natural language processing, Huitzil, et al. (2022) and Qi and Costin (2023) have research on the ontological application of compliance checking and BIM within various domains. Under the approach proposed by Huitzil, et al. (2022), the authors have enriched the BIM model using Uniclass and extraction algorithm to populate the proposed Decret ontology and have utilised DL reasoner to assign instances to the ontology classes.

Zheng et al. (2022) developed the FPBO ontology (Fire Protection for Building Ontology) using the Chinese Code for fire protection design of buildings (GB 50016–2014). The authors have utilised statistic-based methods to extract concepts from the regulatory document, semantic clustering was deployed to merge domain words, and the subsumption method was used to develop a taxonomy structure. The ontology was enriched semantically using SWRL rules to infer implicit information and provide missing information before the checking process. NLP was employed to automate the process of rule interpretation from regulatory documents, label and parse sentences semantically, and align the extracted information with concepts in an ontology for better understanding and automated compliance checking. The unsupervised learning-based semantic alignment method was adopted to automatically align concepts and relations from regulatory texts to those in BIMs or ontologies. The knowledge-informed conflict resolution was introduced to refine this alignment, ensuring that the results are accurate and consistent with domain knowledge.

The study conducted by Jiang et al. (2022) has developed four key ontologies, namely, code ontology (stores knowledge regarding building codes at the same time serving as a TBox), design model ontology, merged ontology and a code compliance checking ontology. The necessary logic is derived through mapping and checking rules. IfcOWL ontology was restructured and ontologies were mapped to cope with ontology heterogeneities and to attain semantic enrichment of the building model at the same time, lowering the processing time. Moreover, the platform proposed by Jiang et al. (2022) is an extensible solution capable of making the domain experts grasp the checking procedure, the semantic gap concerning IFC entities and the concepts of design code can be effectively resolved, an automatic generation is possible for a sub-model that checks the building model for code compliance and the completeness of the information of the building model can be checked beforehand.

One of the major limitations identified by many authors is the need to interpret and develop rules manually. According to Jiang et al. (2022), mapping rules and checking rules related to geometry can be considered complicated and require custom programming. When examining Table 4, it can be seen that several ontologies have been developed to cater the same purpose; however, this could be either due to the unavailability of publicly published ontologies or differences between standards and protocols used in knowledge acquisition as discussed under the sub-section 4.3.1.

Table 4: Ontologies related to compliance checking.

Ref	Ontology	Area Focused	Knowledge Acquisition	Rule Interpretation	Querying	Input	Output	Ontology Development	Ontology Validation	Mapped Ontologies
A	NA	Building accessibility	TEK10 regulation	SWRL	XSLT	NA	NA	NA	NA	ifcOWL
B	Regulations Ontology	Fire safety and accessibility	French regulations	SPARQL queries (geoSPARQL for geometry)	SPARQL	IFC model	Building Collaboration Format (BCF) file reporting	NA	NA	ifcOWL
C	NA	Code compliance	UK Building Regulations Part L	SWRL	SPARQL	NA	NA	NA	Case study	ifcOWL
D	Fire protection for building ontology (FPBO)	Fire protection	Regulatory corpus	SWRL and SPARQL	SPARQL	Enriched BIM model	SPARQL query	Protégé	Pellet reasoner and expert validation and case study	
E	Code Ontology Designed Model Ontology Merged Ontology Code Compliance Checking Ontology	NA	**For code ontology** Regulatory documents Domain experts **For Designed model ontology** Restructuring ifcOWL locally	**Mapping rules** Jena Rules SPARQL queries **Checking rules** Jena Rules SPARQL queries	NA	BIM model	Checking logics, Pre-check results, Checking report	Apache Jena Ontology API	Case study	ifcOWL
F	Decret Ontology	Habitability requirements for buildings	Catalonia's building regulation	Natural Language Processing, Description Logic (DL) Reasoner	NA	Enriched BIM model	Report	Protégé	Prototype	NA
G	Prefabricated component ontology	Design for Manufacture and Assembly (DfMA)	Expert workshop, focus group, interview and peer review	SPARQL	SPARQL	Initial prefabricated Information Model	Finalised prefabricated Information Model	Protégé	Case study	NA

A: Shi and Roman (2017), **B**: Bus et al. (2018), **C**: Beach and Rezgui (2018), **D**: Zheng et al. (2022), **E**: Jiang et al. (2022), **F**: Huitzil et al. (2022), **G**: Qi and Costin (2023; 2022)

4.3.4 Costing and Quantity Take-off

This section provides an overview of the ontologies related to costing and take-off related to construction projects and the identified ontologies are listed in Table 5.

Table 5: Ontologies related to costing and quantity take-off.

Ref	Ontology	Area Focused	Knowledge Acquisition	Rule Interpretation	Querying	Ontology Development	Ontology Validation	Mapped Ontologies
A	Tiling Work Condition Ontology (TWCO) and Tiling Work Item Ontology (TWIO	Searching for the most appropriate work items	Expert knowledge	RETE-based rule engine	SPARQL	Protégé	System output vs experts	ifcOWL
B	Construction-oriented Product Ontology	Quantity take-off	NA	Algorithms	SPARQL	Protégé	Case study	NA
C	Cost Estimating Ontology	Quantity take-off using NRM 1	NRM 1	SWRL	NA	Protégé	Semantic verification: Expert validation Syntactic verification: Pellet reasoner, Manchester OWL syntax validator Case study	ifcOWL

A: Lee, Kim and Yu (2013), **B**: Liu et al. (2016), **C**: Abanda et al. (2017)

Abanda, Kamsu-Foguem and Tah (2017) proposed an ontology for cost estimation based on New Rules of Measurement (NRM). The ontology was designed to be compatible with BIM software tools by integrating IFC nomenclature. Lee, Kim, and Yu (2013) proposed an approach to infer construction work items based on working conditions, where the working conditions are extracted from the BIM model. Further, the study was limited to estimating the cost of tiling work. The study proposed two ontologies, namely, Tiling Work Condition Ontology (TWCO) and the Tiling Work Item Ontology (TWIO). The TWCO ontology was utilised to identify extracted BIM data from IFCXML, such as room usage, building elements, etc. The TWIO ontology defines properties of work items such as tile size, thickness, etc. The construction-oriented product ontology proposed by Liu et al. (2016) focused on developing an ontology for quantity take-off in light-framing building construction. The ontology was developed to extend the BIM schema by adding domain-specific terms and relationships. The ontology is parsed with the BIM model to infer data through an ontology Protégé 4.3 reasoner for quantity take-off. Sigalov (2021) proposed a framework to automate payments between clients and contractors through linked data. The author proposes an information container termed the billing model, which includes the BIM model, billing plan, BOQ and QTO data, and integrates this billing model with blockchain technology and smart contracts to permit an automated payment process.

One of the key observations related to the identified ontologies is that most of them were focused on estimating during the pre-construction stage. However, ontologies related to cost management, reporting, planning, and payment processes during the construction stage are neglected. Furthermore, how ontologies, semantic web, and linked data platforms can be used for cost management related to post-construction, operation, and management stages is not considered. Furthermore, during each project, on a day-to-day basis, a large amount of cost data is being generated, and how this data and knowledge can be put to better use, especially for the governance of future projects using semantic web technologies, is often overlooked.

4.3.5 Design changes

The study conducted by Pilehchian et al. (2015) focused on developing a conceptual framework to track design changes using BIM models in a multi-disciplinary environment. For this purpose, the authors have created an ontology on design changes to illustrate a basic understanding of the characteristics of design changes. The proposed ontology demonstrates relationships between different facets of changes and their impact. The characteristics of changes are categorised into three classes as: object-oriented, adaptation-oriented and integration-oriented. Furthermore, the authors have delved into how the existing BIM tools track changes and identified limited capabilities in detecting spatial, analytical and logical dependencies. Therefore, the authors have suggested a graph-based approach to track and trace dependencies, deduce dependencies from BIM models, and generate dependency graphs. Furthermore, much details regarding the ontology development process are unavailable to provide a technical evaluation of the proposed ontology.

Table 6: Ontologies related to Resource Management.

Ref	Ontology	Area Focused	Knowledge Acquisition	Rule Interpretation	Querying	Ontology Dev.	Input	Output	Ontology Validation	Mapped Ontologies
A	NA	Scaffolding system development using BIM	Taiwan government specifications on scaffolding systems and expert opinion	SWRL	NA	Protégé	Parameters	Inferred results to develop scaffolding system in BIM using Dynamo modules and scaffolding information exported to Microsoft Access to produce the bill of materials	Case study	NA
B	TCI ontology LBS Ontology	TCI utilisation planning	NA	Algorithms	SPARQL Algorithms	NA	BIM model (extracting and parsing data from Revit using Dynamo) LBS data using VICO export and Python. TCI data using the product catalogue.	Dashboard representation	Case study	BOT PRODUCT PROP
C	NA	Collaborative Short-term Planning	Construction and planning knowledge, national and international codes, lessons learned, best practices, contractual terms and strategies, safety regulations, etc.	Drools Java API for SQL rules and SWRL rules	SQWRL	Protégé	BIM model, Machinery and equipment data, Human resource data, Project storage and procurement, etc.	Practical construction plan alternatives and resource packages	Expert verification Internal verification: Pallet semantic reasoner Case study	

A: Feng and Hsu (2017), **B**: Schlachter et al. (2021; 2022); **C**: Tavakolan et al. (2021)

4.3.6 Resource Management

This section provides an overview of the ontologies related to construction resource management, and the identified ontologies are listed in Table 6. The studies conducted by Schlachter et al. (2021, 2022) proposed an approach to use linked data to manage temporary construction items (TCI). The authors have employed rule-based algorithms to extract data from BIM models to determine TCI requirements for each building element. The raw data were collected through BIM models, location-based scheduling systems, and TCI data. These raw data were then exploited in the linked data environment to prepare the TCI utilisation plan with the use of a rule-based algorithm. The authors have utilised three domain ontologies to reflect building data, location-based scheduling system and TCI data, to link data for the generation of the utilisation plan. Building data was expressed through BOT, PRODUCT and PROP ontologies. The authors have developed two new ontologies: 1.) LBS ontology to demonstrate location-based schedule information, which shows the time, process and location of building elements and 2.) TCI ontology presents information related to TCI. However, the currently developed version of the TCI ontology only covers formwork but can be extensible for other TCI.

The study conducted by Feng and Hsu (2017) proposed a BIM-based approach to automatically generate information for assembling scaffolding systems. For this purpose, the authors developed an ontology to interpret field practices in construction sites, which includes classes such as impact factors, scaffolding elements, assembling methods and resources. Tavakolan et al. (2021) proposed a Construction Short-term Project Planning Dashboard (CSP2D) framework, which can assist in collaborative short-term planning during planning meetings. The proposed framework was inspired by collaborative and hierarchical planning concepts from the Last Planner System while concentrating on low levels of planning. The foundation of CSP2D comprises an ontological knowledge base and a decision support system. The proposed Construction Planning and Resource Management Ontology executes complicated multi-variable constraints in an easy and efficient manner to create practical construction plans and resource packages. Compared to previous studies in the same domain, for resource selection allocation, this study deployed a compatibility check against different factors on functional properties and specifications of the resources. Compatibility rules, resource limitations, BIM model (for product information), project information from various project departments (procurement, machinery and equipment, human resources, project control, site and accessibility), and weather formed part of the data sources for the ontology. SQWRL queries were employed to develop alternative plans, which then determine its practicality through SWRL rules. A BIM-based user interface was developed to display results to help the planning team decide pertinent work sequences and resource allocation during collaborative project planning meetings. The study considered only three categories under the ConsResource class, such as labour, material and equipment, while excluding space, safety equipment, etc. Moreover, the study does not consider spatial limitations, possibilities for congestion within the site, safety measures, or assignment of safety equipment and the knowledge base was developed considering only the structural building elements.

4.3.7 Site Monitoring and Control

This section provides an overview of the ontologies related to site monitoring and control, and the identified ontologies are listed in Table 7. The study conducted by Farghaly et al. (2021), Farghaly and Soman (2022) and Farghaly et al. (2024) is inspired by the NASA mission operational control room with the intention of developing a production control room for the construction sites. The cSite ontology for construction programme and production control (CPPC) is concerned with regulating the creation of all deliverables/submittals throughout construction, such as pre-construction submittals, quality documentation, and efforts to progress to the handover stage. Moreover, the user interface of the ontology comprises a dashboard that provides end-users with many features for monitoring and controlling their construction sites in terms of KPIs.

Ren and Zhang (2021) proposed a construction procedural data integration (CPDI) framework to integrate planned construction procedural data from construction procedural documents and executed processes extracted from sensor data at construction sites. For this purpose, the authors have developed a Construction Procedure and Data Collection (CPDC) ontology, which integrates planned construction procedural data with executed sensor data. The CPDC ontology assists in selecting appropriate sensing techniques depending on the activities to be monitored. The CPDC ontology consists of two main modules as construction information and sensing techniques. The current study is mainly limited to extracting construction information from construction procedural documents through NLP techniques.

The study by Martinez et al. (2019) focused on developing an ontological framework for automatic selection tools of quality control specifications for off-site construction manufacturing products integrated with BIM. The proposed ontology consists of three modules, Construction-oriented Product Ontology (initiates the integration with BIM), Manufacturing-oriented Product Ontology (contains knowledge of manufacturing operations), and Quality Control Ontology (contains quality control and assurance information as per various standards, regulations or codes and product-specific company specifications). Through this proposed approach, the users can make SPARQL queries to query quality specifications, which need to be complied with during the manufacturing process.

Table 7: Ontologies related to Site Monitoring and Control.

Ref	Area Focused	Ontology	Knowledge Acquisition	Rule Interpretation	Querying	Ontology Development	Input	Output	Ontology Validation	Mapped ontologies
A	Site monitoring and control	CSite ontology for Construction Programme and Production Control	Field study	NA	SPARQL	Protégé	Aconex (Preconstruction submittals), BIM 360 file (Quality construction submittals), Facility Grid (Handover submittals) and BIM 360 Glue (3D models)	Dashboard representation	Internal validation: Pallet and Hermit reasoner, DL queries and SPARQL queries. Prototype development	NA
B	Site monitoring	No details available								
C	Quality control	Construction-oriented Product Ontology, Manufacturing-oriented Product Ontology and Quality Control Ontology	Liu et al. (2016) on construction-oriented product ontology formulation, Lemaignan et al. (2006) on manufacturing operations and product regulations and codes for quality control ontology	NA	SPARQL	Protégé	BIM data	SPARQL query results	Case study	Construction-oriented Product Ontology and Lemaignan et al. (2006)

A: Farghaly et al. (2021); **B:** Ren and Zhang (2021); **C:** Martinez et al. (2019)

4.3.8 Constraint Checking

This section provides an overview of the ontologies related to constraint checking, and the identified ontologies are listed in Table 8. Soman et al. (2020) proposed a method deploying linked data for constraint checking (LDCC) to model and validate construction schedule constraints (cardinality constraints, logical constraints, precedence constraints, disjunctive constraints, and discrete constraints) to assist the lookahead planning process. The proposed framework architecture is comprised of three layers, namely, the user interface, the processing layer and the ontology layer. The three main types of inputs for the system are; 1.) 4D BIM model, 2.) information necessary to enrich planning data and 3.) constraint information and relationships between attributes and the system provides a feasibility report as the output. The processing layer does three main jobs: 1.) extracting planning data from the BIM model and enrichment of data using detailed inputs from the user, 2.) generation of shape graphs using SHACL (Shapes Constraint Language) vocabulary to define constraints, 3.) validating the shape graph against the data graph to determine constraint violations. The ontology layer provides the data schema for different data types in the LDCC framework, which includes BIM data, constraint data, resource data, etc.) For this purpose, the authors have developed LinkOnt ontology. The authors have employed ifcOWL to extract model information, LinkOnt for resource information and links and SHACL for modelling constraints. Through the LinkOnt ontology, new classes such as sub-activities for ifcOWL, MainActivity, SubActivity, and Sequence, which were unavailable in the ifcOWL, were created. Moreover, the authors have introduced a Resource class in the LinkOnt ontology to link with ifcResource to obtain URIs of geometry and operating requirements. However, geometry-based constraint checking has been disregarded as further research is required to determine how those can be defined as SHACL constraints. Moreover, the knowledge base does not codify disjunctive constraints and discrete resource capacity constraints due to its complex nature. Therefore, even though the system might produce theoretically efficient plans, those might be impractical. Moreover, the proposed system is incapable of integrating short-term, detailed and up to date plans such as lookahead plans and weekly work plans due to the granularity of those documents. Despite existing information models used in the construction planning process having the potential to be a powerful tool for detailed, short-term (look-ahead) planning, these models are currently falling short because they lack the necessary level of detail and clear semantics.

The study conducted by Wang and Song (2015) utilised an ontology to demonstrate construction constraints such as physical constraints, artistic constraints and subjective constraints. The related regulations and progress schedule knowledge are stored in the ontology knowledge base. The structured knowledge in the ontology is combined with the BIM model to generate a construction matrix (MoCC) by extracting building model components and making judgments on component locations. This MoCC matrix is then used to generate construction schedules through a genetic algorithm. However, since the proposed approach mainly considers constraints associated with the geometry, its applicability to real-world scenarios is limited. Yeoh and Chua (2014) developed an ontology to demonstrate construction requirements using the IFC schema. The ontology focuses on three core properties of construction requirements, namely, spatial, ordinal and temporal attributes.

Table 8: Ontologies related to Constraint Checking.

Ref	**Ontology**	**Knowledge Acquisition**	**Rule Interpretation**	**Rule Interpretation**	**Ontology Development**	**Input**	**Output**	**Ontology Validation**	**Mapped Ontologies**
A	NA	DOLCE ontology	NA	NA	NA	NA	NA	NA	ifcOWL
B	Details not available								
C	LinkOnt	Existing ontologies and knowledge about scheduling constraints	SHACL and SHACL SPARQL	SHACL	NA	BIM model Planning data	Validation report	Open BIM dataset	ifcOWL
D	Construction Plan ontology	Benevolenskiy et al. (2012), Tavakolan et al. (2021), Zhang et al. (2015) and Zhong et al. (2015)	SWRL rules (Using SWRLJexx Tab Protégé plugin, SWRL rules are transformed to Jess rule language and executed in Jess rule engine)	SQWRL, OWALPI reasoner queries	Protégé	BIM model, Project-specific constraints Information on project resources (extracted to Excel and parsed using Dynamo)	4D BIM model	Pellet semantic reasoner for internal validation. Case study (expert validation)	Benevolenskiy et al. (2012), Tavakolan et al. (2021), Zhang et al. (2015) and Zhong et al. (2015).

A: Yeoh and Chua (2014); **B**: Wang and Song (2015), **C**: Soman et al. (2020); **D:** Mohammadi et al. (2022)

The study conducted by Mohammadi et al. (2022) proposed an extensible discrete event simulation model that employs an ontological semantic rule engine as a built-in component of a constraint-based simulation engine. The developed framework automatically generates the construction plan by basing the BIM model as the primary source of data. Moreover, the authors have incorporated a construction planning knowledge base by generating SWRL rules and planning constraints. The developed platform can provide alternative activity plans to compare against each other. One of the major drawbacks of the proposed approach is its computationally demanding nature. Moreover, standardised approaches such as ifcOWL were not incorporated in the conversion of BIM information to the ontological format. Furthermore, spatial limitations, site congestion, weather and safety-related measures have not been incorporated, and the study is limited to concrete structures. In a previous study, Mohammadi et al. (2018) proposed an ontological framework to produce a detailed construction method statement with the use of 1.) an OWL knowledge base consisting of information extracted from the BIM model and project resources and specifications that reflect knowledge on the construction process, resources and product, 2.) SQRL rule base to infer new knowledge and for resource assignment.

4.3.9 Logistics Management

Weber et al. (2019) proposed an ontology for the requirements of logistics planning in a large-scale plant construction site by incorporating existing information from the planned 4D BIM model. It particularly focuses on the storage and transportation of various components included in such projects. The proposed ontology is comprised of several main classes such as process (logistic process and assembly process), category (assembly group, assisting tool, building element, etc.), property value, requirement (incorporated twenty pre-determined requirements), requirement value, etc. The authors have pointed out two main use cases of the proposed approach: 1.) requirements necessary for logistic planning can be queried through DL or SPARQL queries, which can be incorporated when creating BIM models, 2.) the ontology can be used to analyse information extracted from the BIM model for logistic planning. One of the major limitations of the study is that it requires some manual efforts to input logistic information and requirements for components. Moreover, the proposed ontology was developed by considering company-specific requirements; therefore, there can be limitations when generalising the ontology for other situations with different boundary conditions. Table 9 illustrates the tools and techniques Weber et al. (2019) used for logistics management.

Table 9: Ontologies related to Logistics Management.

Ontology	Knowledge Acquisition	Rule Interpretation	Querying	Ontology Development	Input	Output	Ontology Validation	Mapped Ontologies
NA	Expert opinion	NA	SPARQL	Protégé	4D BIM model including site layout, manual inputs in logistic information and requirements of components	3D visualisation	NA	NA

4.3.10 Defect Management

Park et al. (2013) proposed a BIM and augmented reality-based proactive defects management approach by utilising ontologies. For this purpose, a Defect domain ontology was developed using defect data collection templates of past projects. The ontology consists of six main classes to demonstrate general information, root cause analysis, impact analysis, control factor analysis, defect description and media information. The ontology can structure, retrieve and utilise defect data for effective and efficient defect management by creating defect management plans. The ontology provides the information required for different stakeholders depending on their requirements.

The study conducted by Lee et al. (2016) adopted a similar approach where the authors proposed an ontology-based framework to capture, structure and analyse construction defect data with the use of context information extracted from BIM models and link data technologies to reduce the recurrence of defects in future projects. As the first step, the authors have collected and analysed defect cases related to waterproofing to develop a standard defect data structure. The ontology was developed based on the findings of this analysis. The required context information is extracted from BIM models. SPARQL queries have been utilised to retrieve and analyse defect data. Table 10 illustrates the tools and techniques utilised for defect management.

Table 10: Ontologies related to Defect Management.

Ref	Ontology	Area Focused	Knowledge Acquisition	Rule Interpretatio	Querying	Ontology Development	Input	Output	Ontology Validation	Mapped Ontologies
A	Defect domain ontology	Construction defect management	Defect data from the defect collection template of past projects	NA	NA	Protégé	BIM model, markers and site AR screenshots	Augmented 3D BIM model	Lab test	NA
B	NA	Sharing defect data using BIM and linked data to reduce the recurrence of defects	Defect data case book	NA	SPARQL	Protégé	Context information from the BIM model	SPARQL query answer	NA	NA

A: Park et al. (2013), **B**: Lee et al. (2016)

4.4 THEORETICAL ANALYSIS – DOMAIN ONTOLOGIES FOR Digital Twin-BASED CONSTRUCTION MANAGEMENT

This section focuses on the implementation of semantic web technologies and ontologies for construction management in the digital twin paradigm. Compared to BIM-based construction management, there were only two studies in the selected set of papers focusing on the digital twin paradigm. The study identified two ongoing digital twin projects, BIM2TWIN (Schlenger et al., 2022) and COGITO (Katsigarakis et al., 2022), both focusing on providing a digital twin platform during the construction stage. Both these projects focus on developing a data schema to enhance the interoperability between data collected through multiple sources and linking across domains.

4.4.1 BIM2TWIN

BIM2TWIN aims to build a Digital Building Twin (DBT) platform for construction management that implements lean principles to reduce operational waste of all kinds, shorten schedules, reduce costs, enhance quality and safety, and reduce carbon footprint. It consists of a (DBT) platform that provides full situational awareness and an extensible set of construction management applications. It supports a closed-loop Plan-Do-Check-Act mode of construction. Under this project, Schlenger et al. (2022) published a data schema for digital twin construction termed BIM2TWIN core ontology. The existing IFC schema only focuses on as-planned BIM models; through this study, the authors have created an ontology consisting of two main modules; as-built and as-performed BIM models, which provide project status information. The ontology consists of four main classes: process, product, resources, and zones. The ontology is currently at a foundation stage, with the core structure defined. However, it would benefit from further semantic enrichment to support more advanced reuse, reasoning and interoperability.

4.4.2 COGITO

The COGITO project aims to "Introduce a real-time digital twin of a construction project by ensuring interoperability among the different components and technologies constituting the digital twin ecosystem, following the lean construction principles. COGITO aims to materialise the digitalisation benefits for the construction industry by harmonising Digital Twins with the Building Information Model concept and to establish a digital Construction 4.0 toolbox" (COGITO, 2021).

The proposed COGITO ontology consists of four modules: Facility module, Process module, Resource module and Quality module (Katsigarakis et al., 2022). The Facility module of the ontology was developed based on the BOT ontology while supporting IFC4x3, which focuses on both building and non-building structures. The Process module was developed without using any previous ontologies and consists of main classes, namely, Process, Task, Cost and WorkOrder. The Resource module consists of Resource, ResourceType and HumanWorker classes. The Quality module consists of Defect, GeometricQualityInformation and SafetyInformation classes.

5. DISCUSSION

5.1 Discussion on Ontology-Based Approaches in Construction

The findings section of the study serves two main objectives; firstly, to provide a brief trend analysis on the review papers examining the year of publication and applied use cases. Secondly, the study explored a theoretical analysis of the identified ontologies. These ontologies were categorised into to two categories; where high level ontologies provide an abstract representation on construction activities facilitating broader application, while domain ontologies section focuses on identifying small-scale ontologies tailored for specific BIM-based construction management tasks.

The trend analysis reveals an increasing interest in ontological applications across multiple construction management domains. The study categorises domain ontologies into ten distinct application areas; construction safety management, 4D BIM, compliance checking, costing and quantity take-off, design changes, resource management, site monitoring and control, constraint checking, logistic management and defects management. Each category reflects targeted efforts to address unique construction needs, showcasing the versatility of ontology-based solutions within the BIM environment.

The theoretical analysis dives deeper into how semantic web tools are utilised to support these application areas, covering approaches for knowledge acquisition, rule interpretation, querying techniques, ontology development platforms, inputs and outputs of the proposed solutions, solution validation approaches and mapped ontologies. This detailed breakdown offers insights into the diversity of techniques employed, which is particularly valuable for researchers exploring ontology-based solutions for construction management.

Table 11 summarises different approaches used in the analysed papers, offering a clear view of the current technological landscape for ontology-based construction management.

The above Table 11 provides an overview of how semantic web technologies have been adopted to deliver different construction use cases. This will assist future researchers in determining suitable approaches to develop similar ontology-based solutions. The widespread use of tools like Protégé for ontology modelling, SWRL and SPARQL for rule and query management, and various APIs and parsers for data extraction indicates a strong reliance on standard semantic web technologies. Moreover, it should be noted that established ontology development approaches should be employed when developing ontology-based solutions, such as Uschold and Gruninger's approach (1996), METHONTOLOGY (Fernández-López, Gomez-Perez and Juristo,1997), Simple Knowledge Engineering Methodology (SKEM) (Noy and McGuinness, 2001), etc. These approaches provide a proper guideline on formulating purpose and scope, conceptualisation, implementation, evaluation and documentation methods for ontology development. Ontology evaluation or validation is a significant phase in the ontology development process, which can be conducted through numerous approaches, as denoted in Table 11, such as automated consistency checking, expert validation, case studies, surveys, prototype development and criteria-based evaluation. Previously formulated competency questions can be used as a reference when evaluating the ontology (Zheng et al., 2021). Selecting the most appropriate method of validation depends on the intended purpose of the ontology.

Mapping and reusing existing ontologies are crucial for building effective, interoperable frameworks. Among the studies reviewed, ifcOWL and BOT emerged as prominent reusable ontologies, frequently mapped to other frameworks. High-level ontologies listed in Section 4.2 offer abstract representations of construction-related concepts that can be foundational when developing ontologies. However, limitations in accessibility, such as the unavailability of published versions of BIMSO and BIMDO, restrict their reuse potential. While the study provides a comprehensive list of current ontologies, it is by no means exhaustive. Many lightweight and abstract ontologies, such as BRICK, SAREF, Building Product Ontology (BPO), Building Element Ontology, PRODUCT, PROP, Time Ontology, etc., offer additional resources and reusable semantics that can be adopted to support activities and tasks throughout various stages of construction projects. Apart from identifying ontology-based solutions for BIM-based construction management, the study also investigated the ontology research conducted on the construction of the digital twin landscape. The study identified two projects, namely BIM2TWIN and COGITO, focusing on developing ontologies for the construction of digital twins.

Table 11: Tools and Techniques Adopted.

Criteria	**Tools and Techniques Adopted**
Ontology development	Protégé
Knowledge acquisition	Regulations and guidelines
	Case study
	Experiments
	Past experiences
	Literature sources
	Expert inputs
Data sources /inputs	BIM model
	Project data
Data extraction	Programming (ex: Dynamo from Revit)
	Using parsers
	Using APIs
Linked data management	Jena Fuseki Triple store
	dotNetRDF Libraries
	FTP server
Rule interpretation	SWRL rules
	Answer Set Programming (ASP) rules
	SPARQL
	RETE-based rule engine
	Algorithms
	Drools
Data processing and querying	SPARQL
	NLP-based query systems
	XSLT
	Algorithms
	Jena rules
	SQWRL
Ontology validation	Automated consistency checking using reasoners (ex: Pellet reasoner, Hermit reasoner)
	Expert validation
	Case study
	Survey
	Prototype development
	Criteria-based evaluation
Output generation	Reports
	4D BIM models
	Enriched BIM models
	Dashboard representation

5.2 Domain Ontologies for Construction Use Cases

The study reveals both the promising areas and gaps in the application of domain-specific ontologies for BIM-based construction management. The study identified five ontologies related to construction safety management, of which job hazard detection, fall from hazards and design for safety were the main areas of focus. For safety management-related ontology development, the incorporation of natural language processing is prevalent to develop ontology-based solutions that comply with the specific rules and regulations. When considering 4D BIM-related ontologies, fewer studies focused on 4D BIM schedule generation and its use cases. Although 4D BIM holds significant potential for construction planning and scheduling, the limited number of studies indicates that this area remains underexplored. A more extensive application of 4D BIM ontologies could offer substantial benefits in dynamically linking construction schedules with building information models, facilitating real-time adjustments and better project management.

Compliance checking emerged as the most researched domain, with a total of seven ontologies identified, primarily focused on accessibility and fire protection areas. Ontologies in this area enable systematic compliance checking, allowing for automated verification of building codes and safety standards. However, the emphasis on accessibility and fire protection suggests that other regulatory domains may benefit from further exploration to create a more comprehensive compliance framework. Ontologies related to costing and quantity take-off primarily focus on estimation tasks, while broader commercial management and quantity surveying tasks, such as payment processing and contract management, have been more substantially explored through other technological approaches like blockchain. This may partly explain their limited research representation in the field of ontology research. Furthermore, blockchain can be considered better suited for financial and commercial management tasks, as semantic web technologies lack built-in mechanisms for trust, immutability and automated execution, which blockchain technology possesses. Only one ontology related to design changes was identified. However, the unavailability of it being published significantly limits its applicability and reusability within the industry. This underscores a broader challenge within the AEC sector, the need for publicly accessible ontologies to support reuse and further development. Three ontologies were identified for resource management, among which two focused on temporary construction items. Even though resource management is a broad area that facilitates efficient allocation and tracking of resources, such as labour, equipment and materials critical for construction project success, the lack of research related to this area needs to be filled. By integrating resource-specific ontologies with BIM data, these frameworks enhance the project manager's ability to monitor resource availability, optimise resource utilisation and mitigate potential delays.

Three ontologies were recorded for site monitoring and control, of which one directly involves overall project monitoring and another study on quality control. However, the main limitation in these studies is the unavailability of published accessible ontologies, which hinders their reuse. Focusing on developing ontology-based solutions combining construction site data, such as visual data and sensor data, with BIM data would enable real-time tracking of site conditions and worker activities. Such integration aids in the early detection of potential delays and deviations from project plans. The study identified three ontologies for constraint checking, focusing on validating the construction schedule. Ontologies can be adopted for constraint checking by defining project-specific rules and constraints, such as spatial, logical, regulatory, etc., enabling automated checks against the BIM model or 4D BIM model in identifying possible conflicts. Ontologies for logistics management enhance the coordination of material and equipment movement on-site, minimising delays and improving workflow efficiency. By utilising ontologies, the project team can synchronise deliveries, track material usage, and manage material storage effectively. Furthermore, ontologies can be applied to support integration with project schedules, enabling alignment of project logistics with project milestones and ensuring that required resources are available in a timely manner. The study identified two ontologies related to the defect management domain, both of which focus on structuring defect data to improve quality control. Despite aiding in tracking defects, these ontologies are limited to specific defect types. Expanding these ontology-based approaches to cover diverse defect scenarios would enhance their utility in proactive quality management. While the reviewed ontologies contribute greatly to BIM maturity, automation, interoperability and integration, several areas remain underexplored. A more comprehensive, accessible suite of ontologies across diverse domains will be essential in realising the full potential of BIM-enabled digital construction management.

5.3 Transition Towards BIM Stage 3

The reviewed ontologies within this study contribute significantly toward achieving the industry's shift towards BIM Stage 3 Maturity. Rasmussen et al. (2020) identified basic requirements and characteristics of BIM Maturity Level 3, namely, web-based information exchange, collaborative workflows, interoperability, flexibility, data-level integration and tracking. The ifcOWL ontology has laid a foundational step toward BIM Stage 3 by converting the

IFC schema into a machine-readable OWL format, which supports data exchange on the web. However, due to the inherent complexity of the IFC schema, the W3C Linked Building Data (LBD) community developed modular ontologies such as BOT and PRODUCT to enable lightweight, interoperable solutions. These modular ontologies align with the BIM Stage 3 requirements of allowing various systems to connect and exchange data efficiently across different domains, providing a flexible, web-based framework for BIM integration. The DiCon ontology is designed to integrate data from multiple ICT platforms, making it highly adoptable for web-based information exchange. Dicon's ability to align various datasets across construction processes and project entities enables a robust, interoperable data environment essential for BIM Level 3. Moreover, integrating with other well-established ontologies like ifcOWL and BOT helps Dicon to maintain data consistency and supports collaborative workflows across disciplines. The SHE ontology facilitates real-time safety management by linking safety data with BIM models, thereby allowing proactive risk management. Furthermore, its alignment with ifcOWL assists in providing standardised semantic structures that facilitate cross-platform data exchange and machine readability. Ontologies like the 4DCollab ontology and the Claim4D-Onto ontology assist in integrating spatio-temporal data into BIM models and improve collaboration.

Digital twin-focused ontology projects like BIM2TWIN and COGITO extend BIM capabilities by structuring semantic representations of project data. While these projects support integration of planning data with as-built data, the incorporation of real-time IoT updates is generally handled through system-level integration mechanisms rather than ontology-based modelling, given the known limitations of ontologies in processing high-frequency sensor streams. Such projects align with BIM Level 3 objectives on live project data integration and a data-centric approach for proactive decision making. The TCI ontology facilitates efficient resource management by linking BIM data with inventory systems. In addition, the integration of BOT and PRODUCT ontologies with TCI allows seamless data flow between scheduling systems, material inventories and BIM models, exemplifying the data fusion needed to achieve web-scale interoperability. Moreover, compliance checking ontologies such as the Fire Protection for Building ontology and Regulations Ontology demonstrate how automation can enhance BIM Stage 3 capabilities. By integrating rule-based compliance checks directly with BIM workflow, these ontologies automate the verification of regulatory requirements in a data-centric manner. Therefore, it can be stated that the reviewed ontologies collectively contribute to BIM Maturity Stage3 by advancing structured data integration, facilitating interoperability and enabling automation across construction management tasks.

5.4 Challenges and Barriers

This section highlights the barriers in implementing ontology-based solutions in the BIM or Digital Twin environment. One critical barrier in advancing ontology-based solutions within the construction sector is the limited availability of published, accessible ontologies. This hinders the reuse of developed ontologies and collaborative advancement. While some high-level and established ontologies like ifcOWL and BOT are available, many other ontologies developed for task-specific applications remain unpublished. Openly accessible ontologies are vital to facilitate standardisation, interoperability and the development of comprehensive ontological frameworks that can be reused across different construction projects and software platforms. This can be seen in the findings chapter, where it is noticeable that there are several ontologies developed to cater for the same use case, causing redundancies. This redundancy is largely driven by the unavailability of openly published ontologies and the fact that some researchers often abstain from publishing and sharing the ontologies they develop. The main reason would be the unavailability of published ontologies.

Scalability remains a complex issue for construction management ontologies. Although this study does not directly address big data handling, scalability here refers to the ability of ontologies to support the diverse, interconnected data requirements encountered in construction execution. These challenges include managing complex data relationships generated by multiple stakeholders throughout the project lifecycle, integrating heterogeneous data sources with standardised protocols across the AEC industry and lacking consistency in data definition, leading to difficulties in deciding which information needs to be shared at different project stages. The multifaceted nature of these challenges suggests that current ontologies lack the necessary flexibility to seamlessly scale to larger, dynamic data environments in construction. Further research is required to develop modular, lightweight ontologies that can accommodate diverse data demands while maintaining performance.

Ontology mapping is a crucial step in developing domain ontologies and has been established as a best practice by W3C to reuse existing ontologies in developing new ontologies. However, there are several challenges which hinder this process.

1. Challenges associated with ifcOWL: ifcOWL ontology can be considered a core ontology for the AEC industry. The comprehensive and complex nature of ifcOWL impedes its direct usage for various use cases in the construction industry (Herrera-Martin et al., 2022). This complexity creates a difficulty in extracting only the relevant information needed for lightweight or task-specific applications. In order to address this, many researchers tend to introduce an intermediate mapping process that translates IFC-based data into simplified semantic models tailored to particular domains, thereby improving and streamlining the usability and knowledge extraction.

2. Semantic discrepancies and heterogeneity between different ontologies: Different ontologies may cover the same concepts but may define and relate concepts differently. The heterogeneity is mostly generated by conceptualisation incompatibilities between various conceptualisations of the same domain (Davies et al., 2006).

3. Difficulties in identifying existing ontologies relevant to the domain, as there is no proper mechanism to search and retrieve relevant ontologies. Some ontologies are not published online for public access, limiting their reusability. When considering ontologies listed under Table 1 and Table 4 of Section 4, it is clear that there are a number of ontologies developed to cater for the same purpose. This could be due to the unavailability of published ontologies, which can be reused to prevent redundancies.

5.5 Future Research Avenues

5.5.1 Ontology Reusing, Merging, Mapping and Alignment

Ontologies can be mainly categorised into two types as core ontologies and domain ontologies (Schlenger et al., 2022). Core ontologies are highly abstract ontologies that illustrate concepts related to a specific field or practice (Van Engers et al., 2008). In contrast, domain-specific ontologies illustrate concepts related to niche areas (Rasmussen et al., 2017). In the construction sector, ontologies such as ifcOWL, BIMDO, and BOT, which mainly focus on describing building topology, can be considered core or high level ontologies. Other domain ontologies can be developed by reusing or aligning with the existing core ontologies. As per W3C (2021) best practice guidelines, existing ontologies and vocabularies should be reused to enhance interoperability and minimise redundancies. When considering the analysed ontologies in this study, some ontologies have repeatedly used the same concepts without using existing ontologies to define them, ultimately leading to interoperability issues and redundancies. However, it should be noted that some studies have used ifcOWL or BOT ontologies in defining their domain ontologies, which can be considered a positive tendency. Therefore, researchers involved in knowledge engineering research are encouraged to reuse existing ontologies as much as possible when developing new ontologies.

5.5.2 Developing best practice guidelines to streamline the ontology development process in the AEC industry

When examining the research trends in the AEC industry, a positive trend can be seen towards semantic web technology-related research. However, as mentioned previously, there are numerous barriers that limit harnessing the benefits of semantic web technologies. Proper initiatives should be implemented to search and retrieve existing ontologies to encourage reuse, and the lack of guidelines and resources related to the ontology development process in the AEC industry needs to be addressed.

5.5.3 4D BIM Applications

4D BIM can be an effective resolution to many issues within the current construction planning process (Sheikhkhoshkar et al., 2019). 4D BIM comprises of numerous use cases such as site analysis, including temporary structures, spatial clash detection and workspace congestion prevention, site monitoring (including work done, work in progress and layout design), spatio-temporal analysis, planning of evacuation paths, logistic management, resource management including, material, labour and equipment, waste management, etc. (Doukari et al., 2022). Despite the potential of these use cases, their full potential has yet to be realised in the execution of construction projects. Integrating semantic web technologies into 4D BIM use cases offers a pathway to significantly enhance interoperability and introduce sophisticated reasoning capabilities. Therefore, researchers are encouraged to explore the applicability of semantic web technologies for unexplored 4D BIM use cases.

5.5.4 Construction Planning and Delivery

The study conducted by Schlachter, Rasmussen, and Karlshoj (2022) proposed a framework and a case-study-based design solution for deploying ontologies and linked data for TCI planning. The authors have further addressed and proposed a framework for future scenarios to a process map for enhancing construction through data-driven and integrated project delivery. Similarly, with the improved tendency towards deploying concepts like the semantic web and linked data in the construction industry, construction project planning and project delivery can be made more data-driven and decentralised among different stakeholders.

5.5.5 Application of Semantic Web Technologies During the Construction Phase or the Whole Lifecycle

Given that a construction project generates a vast quantity of data daily across various facets in a variety of formats throughout its life cycle, there is a significant opportunity to leverage semantic web technologies and linked data for enhanced utilisation of this information. Exploring how these technologies can be applied during various phases of construction projects could unlock further opportunities and benefits. This approach not only promises to improve the efficiency and effectiveness of managing and utilising construction data but also offers the potential to extend the lifecycle of buildings and infrastructure through better-informed decisions and practices.

5.5.6 Construction Progress Monitoring

Automated construction progress monitoring stands as a pivotal aspect of modern construction management, offering the potential to significantly improve efficiency and accuracy. Given the diversity of mediums and sources from which progress data can be collected, often in heterogeneous data formats, the application of semantic web technologies and linked data emerges as a powerful tool strategy to integrate a comprehensive overview of construction progress. This could be achieved by identifying how data flow from IoT devices can be semantically linked to BIM or Digital Twin models to track progress in real-time.

5.5.7 Digital Twins

The feasibility of a digital twin relies on the capacity to represent data and its semantics accurately and make the complete data sets accessible for knowledge processing (Boje et al., 2020). Therefore, ontologies play a crucial role in developing digital twin platforms, serving as the backbone for data representation and interoperability. Although many current digital twin implementations do not yet rely on ontologies, the integration of semantic web technologies holds significant potential to advance their functionality and scalability by enabling consistent data representation, semantic interoperability, and intelligent knowledge processing. Figure 5 demonstrates how semantic web technologies can be utilised for digital twin construction. It illustrates the interaction between the physical and virtual environments in a digital twin ecosystem, structured across three layers: physical environment, data layer and virtual environment. In the physical environment, data is continuously collected from the physical world through various sources such as IoT devices, sensors, different systems, reports, monitoring devices, etc., capturing real-time or near real-time data about the project status, including progress, resource consumption, environmental conditions, etc. The data layer focuses on data processing and analysis functions. Data collected from the physical environment is first handled by the data processing component, which transforms raw information into structured data suitable for integration and further analysis. The data analysis component uses this processed data to generate insights for monitoring and decision-making. This process relies on semantic web technologies, ontologies and linked data to ensure that data is interoperable. These technologies enable consistent meanings and relationships between data components, enhancing the ability to analyse and interpret complex data sets accurately. In the virtual environment layer, a digital representation of the physical asset is created through continuous updates reflecting the latest information collected from the physical asset. The interaction between the data processing and analysis components enables a feedback and intervention flow.

The study identified two ongoing research projects based on developing construction digital twins, where both studies focus on developing data schemas. In the BIM2TWIN Core ontology developed by Schlenger et al. (2022), only the domains and ranges of object and data properties have been defined so that this ontology can be used in the ontology mapping process to create domain ontologies. COGITO is a core ontology that is still not publicly available, though it holds the promise for developing domain ontologies tailored for various digital twin applications. Furthermore, incorporating IoT devices and sensing technologies is a crucial part of digital twins that has not been properly paid attention to. Moreover, the potential of semantic web technologies to enhance data integration and analytics within the digital twin framework is a rich area for further investigation. This approach could significantly advance the functionality and utility of digital twins, offering new avenues for data management, analysis, and application in real-world scenarios.

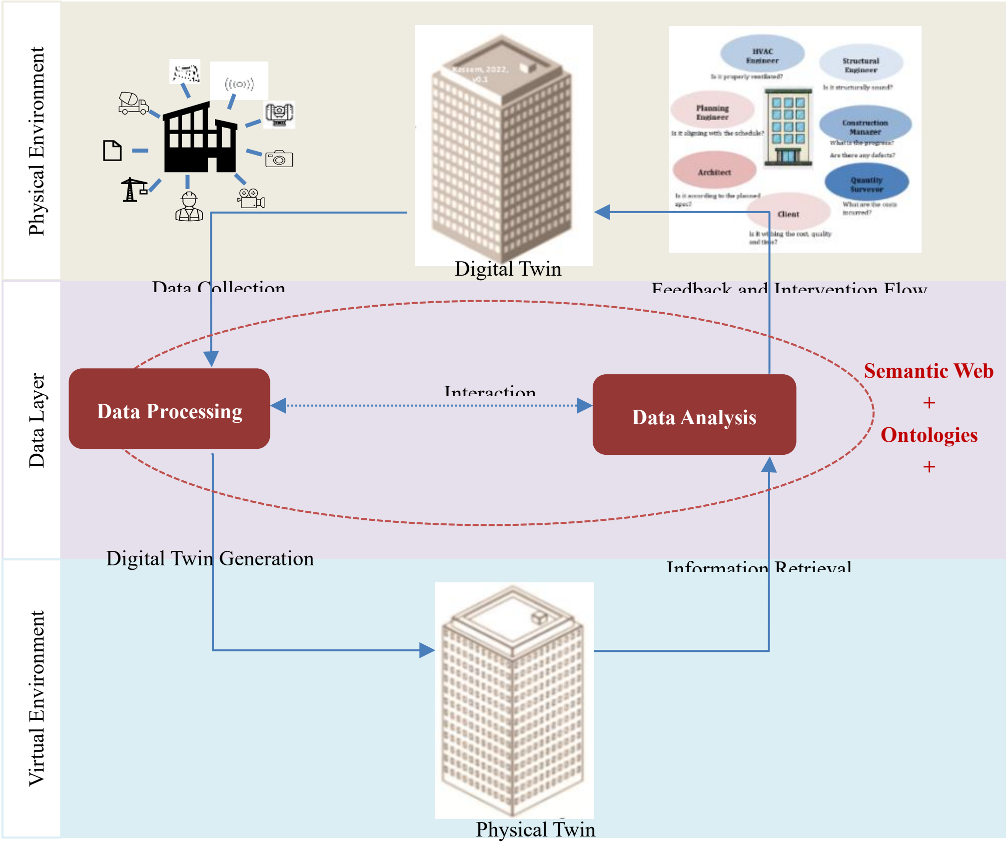

Figure 5: Semantic Web and Digital Twins.

6. CONCLUSIONS

This study offers a comprehensive analysis of the utilisation of semantic web technologies, ontologies, and linked data for construction management use cases in BIM and digital twin environments. Employing a systematic literature review combined with a brief trend analysis, the research highlights a notable inclination towards developing BIM-based domain ontologies for various construction industry applications. The study identified ten application areas of semantic web technologies in the construction management paradigm, such as safety management, compliance checking, site monitoring and control, 4D BIM, resource management, etc. These ontology-based solutions highlight the versatility of their application.

The analysis demonstrates the growing potential of ontologies to address specific construction needs and streamline processes. For example, compliance checking ontologies automate the regulatory verification process, safety management ontologies assist in proactive hazard detection, and 4D BIM-related ontologies demonstrate a promising future in automating construction scheduling and determining schedule adherence. Moreover, digital twin initiatives such as BIM2TWIN and COGITO demonstrate the use of high level ontologies to support real-time data integration and decision making, providing a groundwork for future digital twin applications in the construction sector.

The findings suggest that the reviewed ontologies make a significant contribution for shifting towards BIM Stage 3 Maturity by facilitating structured data integration, interoperability and automation. Well established ontologies such as ifcOWL and BOT provide foundational structures that enable web-based information exchange. However, reaching full capacity of BIM Stage 3 Maturity will require a more comprehensive suite of accessible, interoperable ontologies that address a broad range of construction management tasks.

The main limitation with most of these ontologies is that they have been unpublished, hindering their reuse and integration with other ontologies in developing an ecosystem of ontologies. Challenges associated with ontology mapping and reusing existing ontologies can be recognised as a key challenge in ontology research. Apart from BIM-based ontologies, there are numerous other construction industry-related ontologies that are not documented well in a central repository that researchers can refer to when developing new ontologies. To advance the application of ontologies in BIM and digital twin, future research should focus on adhering to best practices in ontology development and reuse, expanding domain-specific ontologies, integrating IoT and real-time data into BIM and digital twin models and exploring scalable data solution that supports larger and complex project data environments.

The findings of the study are limited to papers extracted during April 2023 from Scopus and Web of Science databases. Furthermore, only the studies related to building construction during the construction execution phase have been considered, and the studies related to infrastructure projects have been disregarded. Due to these limitations, not all aspects of the integration of semantic web technologies for BIM or digital twin-based construction management may have been covered.

In summary, it can be stated that there is a growing interest within the construction community and a promising future in applying semantic web technologies and linked data for BIM-based and digital-twin-based construction management. Therefore, this study can be used as a source of reference for both researchers and industry practitioners to gain insights into existing studies and ontologies related to construction management in BIM and the digital twin realm. This study provides an overview of the semantic web tools that have been utilised to provide ontology-based solutions, the limitations within those solutions and the future directions for research.

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