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BIM ontology for information management (BIM-OIM)

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ABSTRACT

The adoption of Building Information Modelling (BIM) in the construction industry has been hindered by numerous barriers, notably the limited understanding of its concepts, protocols, and the intricate interplay between processes, people, and technologies. To address these challenges, a range of standards and guidelines have been developed, most notably the ISO 19650 series, which offer a comprehensive framework for implementing various aspects of BIM in construction projects. However, despite the BIM's collaborative philosophy, the standards and specifications that guide its adoption and implementation seldom reveal and explain the relationships between their key elements and concepts. This lack of clarity limits understanding and undermines the very essence of collaboration that BIM seeks to promote in construction projects. The text-based nature of the standards and specifications makes it difficult to identify common concepts that cut across the different project phases, their relationships, and interdependencies. This study proposes a BIM ontology for information management (BIM-OIM) that makes BIM process data more available and easily useable, allowing other researchers and practitioners to implement, and extend its use within their domains of practice. To achieve the practice-driven goal of BIM-OIM, Yet Another Methodology for Ontology (YAMO), one of the leading ontology engineering methodologies, was used to develop BIM-OIM. BIM-OIM is a formal and structured representation of ISO 19650 knowledge that is machine-processable. This representation enhances understanding, promotes reusability, and supports practical applications throughout the information management lifecycle. Key applications include the development of BIM Execution Plans, compliance checking for information containers, and identifying the roles of various stakeholders within a project.

1. Introduction

Poor data and information management significantly impact the construction industry's financial outcomes and operational efficiency. In 2018, the US construction sector anticipated spending $177.5 billion on labour costs for sub-optimal activities, demonstrating the high cost of inefficiencies such as time spent searching for project data/information and resolving conflicts [1]. Furthermore, communication challenges and inadequate technology usage compounded these issues, costing the US construction industry over $31 billion in 2018 due to miscommunication and inaccessible information [2]. Globally, the construction industry faced a staggering $1.85 trillion cost in 2020 due to "bad data, " leading to substantial rework costs and inefficiencies [3].

These systemic issues highlight the critical need for robust data management and communication strategies to mitigate the

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substantial inefficiencies and cost implications. Across the world, the industry is known to be challenged by inefficient information exchange, a lack of knowledge sustainability, overall fuzzy communication lines, and poor information management. Structured data and knowledge modelling present an opportunity to transform construction industry processes significantly. As highlighted by Autodesk [4],"adopting a data strategy can provide a competitive edge by eliminating many avoidable costs, both direct and indirect. Making informed decisions based on "good" data improves organisations" performance, positioning them as leaders in the construction sector [4].

Building Information Modelling (BIM) has been demonstrated as a potential solution that could facilitate improved data and information management, more effective communication, and enhance knowledge sustainability, not only as a technological innovation but also as a tool for positively influencing the integration and collaboration processes [5–8]. With increasing ubiquity across the world, it has become imperative for governments such as the UK to mandate the implementation of BIM for all public sector projects; this creates and maintains its status as a 'best practice country' [9]. However, the adoption of BIM in the UK construction industry has been slow since this mandatory implementation policy has been in place [10,11]. Many issues have been identified as responsible, including high costs, lack of knowledge, and insufficient training (El Hajj et al., 2023).

Several solutions revolving around information aggregation, standardisation and interoperability have been devised to address these issues [6–8]. Formalised BIM standards have introduced much-needed structure and coherence to an otherwise disorganised and fragmented construction information technology ecosystem. Abanda et al. [12] utilised process models to interpret the ISO 19650 standards, improving comprehension and providing deeper insights into their practical implementation. Codifying knowledge using ontologies can significantly enhance machine readability and improve understanding and interpretation of the meaning of unstructured information [13–15]. BIM standards ontologies can ensure that BIM information is human-readable and machine-processable. They enable the creation of a shared language and structure for representing data, making it accessible and understandable to both humans and computer systems. This dual readability supports the accurate and efficient interpretation of information, a critical factor for the success of BIM projects across diverse platforms and stakeholders. This aligns with the recent HM Government initiative that recommended digitising standards and specifications so that requirements are both human and machine-readable. Furthermore, it will facilitate cross-referencing with other standards and process workflows [16]. Several BIM standards and guidelines have been developed to ensure the creation, sharing, use and storage of asset information throughout its lifecycle is uniform and understandable by all parties involved at every stage. Many of these standards are inevitably related, although their links are not immediately evident and explicit. The interconnections are many including cross-referencing of templates of deliverables generated as outputs, specified by the different standards.

However, like most standards, BIM standards are typically documented in natural language, non-machine readable, which can be confusing, difficult to understand and challenging for professionals to grasp and implement effectively [17–20]. Varied interpretations of these standards can significantly impede communication and information interoperability among collaborating parties, thereby diminishing the standards' effectiveness. This is even more so as the underpinning principle of BIM emphasises human collaboration and processable information with less emphasis on machine-processability of ISO 19650 information.

This problem has caught the attention of some researchers. For instance, in a recent study, Filardo et al. [20], predicated their study on the semi-structured textual nature of standards documents and the difficulty in describing information requirements in machine readable format that practically supports information delivery. In effect they developed an ontology to define information exchange requirements, providing interoperable data, and data validation. Their framework focused on the modelling of the level of information need, a part, albeit important, of the information delivery framework described in the ISO standards documents. They based their work on ISO 23386, 23387 and 7817 to develop a formal semantic description of information requirements. They acknowledge that parts of the standards are already available in XML and ontology schemas and sought to align and improve them.

In practical applications or implementation of BIM, there remains a challenge of developing a current, standard list of elements that should be incorporated into a BEP at various stages of project procurement and delivery [21]. Additionally, there is a paucity of studies aimed at representing knowledge about BIM standards and specifications from an ontological perspective. The most recent and important [20,22,23] ones have covered significant grounds but leave some gaps more so in holistically capturing, representing and operationalising knowledge in the BIM standards covering five main domains of knowledge including the information container, project processes, technology, actor roles in delivering a construction project.

To achieve this aim, the study sought to.

- identify the key concepts in BIM standards and specifications, including their relationships and dependencies, and develop an ontology that captures these elements.
- develop reasoning rules for the ontology (BIM-OIM)
- evaluate and validate the ontology using ontology reasoners and experts

The remainder of the article begins with an exploration of Ontology Engineering (Section 3), laying the groundwork for understanding the principles and methodologies involved. This will be followed by an Overview of BIM Ontologies (Section 4), where existing BIM ontologies are reviewed. The Research Methodology (Section 5) section outlines the design, methods, and tools used in the study. Subsequently, the Development of the BIM-OIM Ontology (Section 6) will be detailed, explaining the conceptual framework and integration of ISO 19650 standards. Implementation in Software Environments (Section 7) will then be discussed, highlighting practical applications. The BIM-OIM Applications (Section 8) section will illustrate various use cases, followed by the BIM-OIM Evaluation (Section 9), which assesses the ontology's effectiveness. The article will conclude with Findings and Discussions (Section 10), summarising the key insights, and a Conclusion (Section 11) that encapsulates the overall study outcomes.

2. Building Information Modelling (BIM) implementation ecosystem

The National BIM standard of the United States defines BIM as a "digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle; defined as existing from earliest conception to demolition" [24]. Similarly, according to ISO 19650, BIM uses a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions [25]. BIM is essentially implemented within an ecosystem of interconnected component elements made up of technological and security infrastructure tools, people (implementers and persons involved or impacted by the implementation), policies, standards, legal guidance, and the processes and protocols, either prescriptive or bespoke, informed by them [26]. These define the implementation framework and methodology. Explicitly defining these components within the context of this study is important as it forms the foundation for modelling them.

2.1. Defining components of the BIM implementation ecosystem

2.1.1. Technology

BIM rightly recognized as a process and at the core of BIM processes for delivering built assets are the technological tools that facilitate the process or enable their implementation [26,27]. BIM technology refers to the system of software and hardware tools and platforms used to create, manage, and secure building asset information. These technologies enable the collaborative creation, sharing and storage of digital representations of physical and functional characteristics of spaces, buildings etc., and also supporting simulation, analysis, and visualization at various stages of the project lifecycle. BIM allows for complex data to be handled in a more integrated and efficient way, promoting collaboration among all project participants. The language used for describing BIM technology has evolved over the years. For example, the concept known as 'Common Data Environment' as in the ISO 19650 has evolved into a more generic 'Information Management Platform' as in the UK BIM Framework guidance [28]. In this study, for consistency, the concepts used, and definitions are drawn directly from the ISO 19650.

Implementing BIM requires transparency and more open ways of working through information management platforms and other means that may contain sensitive information such as confidential information, trade secrets and personal data of parties involved (ISO 19650-5). These platforms and other tools are vulnerable to cyber threats, and responsible parties must be security-minded (ISO 19650-5, 2019) by applying appropriate and proportionate security measures to ensure compliance with data privacy laws and protect against unauthorised access, use or disclosure of information. This makes it necessary to ensure the appropriate cyber security tools and protocols through governance structures, accountability and a responsible approach ([29]; ISO 19650-5, 2019).

2.1.2. Process

The ISO 19650-1 defines the delivery phase of projects as part of the lifecycle during which the building asset is designed, constructed and commissioned. This represents the scope of the construction or delivery phase process. Within this process, actors collaborate in the production and management of information. BIM is a process for creating and managing all information related to a construction project throughout its entire lifecycle ([26]; ISO 19650-2 2018). It involves generating and managing shared digital representations of physical and functional characteristics of construction objects and spaces. Integrating BIM processes into traditional construction workflows can be challenging, as it requires changes in work practices, standards, and protocols [30,31]. Ensuring that all stakeholders are aligned and cooperative throughout the project's lifecycle is crucial but often difficult.

2.1.3. People

The human aspect of BIM involves the various professionals and stakeholders who implement the BIM process and technology. This can include architects, engineers, contractors, owners, and facility managers and are described as actors in the ISO 19560-1 2018 as 'persons, organisations, or organisational units involved in a construction process'. People are crucial for the successful implementation of BIM, as their collaboration, cooperation, communication, skills, and determine the effectiveness of BIM processes.

2.2. BIM implementation standards, protocols and guidance documents

The unstructured and often problematic nature of BIM implementation across the world necessitated the creation of standards and protocols to guide its implementation. The ISO 19650 is a suite of international standards aimed at providing guidance and an approach for information management throughout the whole lifecycle of a built asset using Building Information Modelling (BIM). These documents standardise and streamline data and information management across project stages, from design through construction to asset management, creating a collaborative and efficient environment capable of reducing direct and transactional costs and saving time. ISO 19650 suite has several parts, with the first two being particularly essential for the delivery phase of construction projects.

ISO 19650-1 outlines the concepts and principles for information management across assets' delivery and operational phases. This part of the standard defines the concepts associated with information creation, use, sharing, storage and transfer, removing barriers to collaborative working, enhancing competitive tendering across borders, and reducing risk and cost through asset and project information models.

ISO 19650–2 details the information management process, specifically during the delivery phase of assets, helping define the information requirements and establishing a conducive collaborative environment for information production and usage on projects.

Conformance with ISO 19650 allows organisations and stakeholders to collaborate efficiently and consistently with other team members in information management processes, regardless of their geographical location. This standardisation is crucial for generating and classifying data, ensuring data security, and facilitating data exchange. Implementing ISO 19650 involves agreeing on a common data environment (CDE) where all project information is produced against agreed standards. This ensures that information can be used and reused throughout the asset lifecycle without the need for translation or loss of integrity. Ensuring consistency and efficiency across project teams requires consensus on terms, acronyms, units, and other essential standards.

Amongst the requirements of ISO 19650, the pre-and post-appointment BIM Execution Plans are two main important documents required for managing BIM-compliant projects. Working in a collaborative environment requires a clear definition of obligations, the methodology for how building information models are to be produced by the project team, and how the models are to be used. Thus, it is imperative to establish “protocols” that address the aforementioned parameters.

2.2.1. Pre-appointment BIM execution plan

At the project level, it is essential to have a document that operationalises the standards and details the proposed plan for executing BIM throughout the project’s lifecycle. The Pre-Appointment BIM Execution Plan is prepared before the appointment of the supplier (contractor, consultant, or design team) and is typically submitted as part of a tender or bid proposal. It demonstrates how the prospective team plans to deliver BIM in accordance with the Employer’s Information Requirements (EIR). The BIM execution plan proposed in the ISO 19650 in response to exchange information requirements (EIR) serves this function. The EIR is a crucial document that presents the appointing party’s aims and purposes for the information asset produced. A prospective Appointed Party prepares the pre-appointment BIM EP (also known as BEP) to present how they would comply with the EIR. In addition, it shows their capability, capacity and approach to applying the BIM project. It is submitted first before the appointment or contract is awarded to explain the Appointed Party’s methodology for delivering the EIR. Hence, the Pre-Appointment BEP has become, for BIM-enabled projects, an essential shortlisting requirement during the procurement process.

2.2.2. Post-appointment BIM execution plan

The Post-Appointment BIM Execution Plan is developed after the contract has been awarded. It builds upon the Pre-Appointment BEP but now includes specific, detailed execution strategies aligned with the appointed team’s workflow. Drawing also from the ISO 19650, this document can be described as a product of the continuous development of the Pre-Appointment BIM EP. After the Appointed Parties’ contract award, they would provide additional documents and information in response to the requirements detailing the practical implementation of the suggested methodology in the Pre-Appointment BIM EP. The Post-Appointment BIM Execution Plan should, therefore, include the following information after the award.

2.2.3. Protocol

A protocol is defined as “The accepted or established code of procedure or behaviour in any group, organisation, or situation” (OUP, 2016). In the context of BIM adoption, a protocol is typically needed to define responsibilities and accepted BIM implementation practices within which the guidelines to be followed are established [32]. The CIC BIM Protocol, 2nd Edition, represents a significant update from its 2013 predecessor, reflecting advancements in BIM-related standards and practices since its initial release. It remains the only contractually relevant BIM protocol in the UK. The CIC BIM Protocol outlines specific obligations, identifies the building information models required to be produced by the project team, and establishes how these models should be managed and utilised throughout the construction process.

2.2.4. Policies

The policy aspect of BIM refers to institutional level guidance and mandates established by government bodies, industry associations developed collaboratively with relevant private organisations that inform the standards, guidance and regulations on BIM [26]. These policies are designed to ensure that BIM is implemented effectively and consistently to improve the quality, efficiency, and sustainability of built environment projects. They may cover various areas, including data management standards, interoperability requirements, level of detail specifications, and roles and responsibilities among project stakeholders.

2.3. Legal implications and protections against legal liabilities

2.3.1. Legal implications of BIM

Construction projects are complex, time-intensive, resource-dependent and often adversarial endeavours that require clearly defined roles, responsibilities, and liabilities within a legal framework. With the adoption of BIM, establishing such a framework becomes even more critical [33]. Apart from the legal liabilities arising out of collaboration in a project setting, the collaborative production and exchange of information make for joint and several liabilities for things like errors in design and procedural errors, among others, like copyright infringements as are the result of access or usage of information produced by others. Consequently, any unauthorised use can lead to legal action.

Violating software licence agreements can also result in legal problems [29]. The parties involved in a project must negotiate and agree on the legal framework for implementing BIM, Covering critical issues like intellectual property rights, roles and responsibilities among others [33,34]. BIM information requirements and responsibilities must also be written into construction contracts, and in fact, construction contracts must be written in such a way that it gives legal validity to appended BIM Execution Plans and protocols.

2.3.2. Insurance

Professionals and team members with information production and management responsibilities must produce information that is suited to the purpose for which it is required and with a reasonable level of care [35]. As is typical with other professional services provided on construction projects, an insurance policy is a common way to protect against the consequences of a contract breach in this regard. Similar to a Joint Names Policy for construction contracts, an Integrated Project Insurance Policy, for instance, offers collective coverage for all project participants, addressing the shared responsibilities and risks inherent in BIM projects. The complexity of BIM, involving detailed digital representations of a project's physical and functional characteristics, introduces various risks ranging from data breaches to professional errors, necessitating specific insurance solutions. Professional Indemnity Insurance (PII) is critical as it covers damages caused wholly or in part by the acts or errors of project participants. Moreover, BIM introduces emerging risks that current insurance policies may not explicitly cover, making developing BIM-specific insurance products essential.

Besides Professional Indemnity Insurance, which covers legal costs and damages for professional errors, other relevant types include Cyber Liability Insurance for data breaches and cyber-attacks and Construction Cost Insurance, which benefits from BIM's accurate project visualisations to provide reliable coverage for construction costs. These insurance products play a critical role in managing the risks associated with BIM's collaborative, data-intensive processes, ensuring that all parties involved are protected against the unique challenges of modern construction projects. For example, a Joint Names Policy that equally indemnifies contracting parties regarding their liability for damage to physical and technological equipment and infrastructure may also be important, especially in a collaborative project environment.

3. Ontology engineering and semantic web

An ontology is a formal representation of a set of concepts within a domain and the relationships between those concepts [36]. It is made up of classes, their properties, and individuals, which are instances of classes. Ontology engineering is the systematic and structured process of creating, defining, and maintaining ontologies. Furthermore, ontology engineering involves various steps, including defining the scope of the domain, specifying concepts and their relationships, choosing appropriate representation languages, and ensuring the ontology's accuracy and relevance to the domain [14,17,37,38]; [null]. In this context, an ontology is a formal, explicit description of concepts, properties, and relationships within a specific domain of knowledge.

Many methodologies for building or developing ontologies exist in the literature, including YAMO, METHodology for ONTOlogy (METHONTOLOGY), and Simplified Agile Methodology for Ontology Development (SAMOD). These methodologies use ontology languages, which are a formal means to represent knowledge in a structured and systematic manner, facilitating reasoning and applications across various domains. Some examples are Web Ontology Language (OWL), Ontology Markup Language (OML), OntoUML and RDF SHapes Constraints Language (SHACL).

Additionally, modelling ontologies can be quite cumbersome and challenging to document. Several applications, including common software like Karlsruhe ontology (KAON), OntoClean, HOZO, Protégé-OWL, TopBraid Composer, and DogmaModeler, can simplify this process. The aforementioned methodologies, languages and software have been critically reviewed [39–41]; hence, their efforts will not be duplicated here.

These tools and methodologies play a crucial role in supporting the development and implementation of frameworks like the Semantic Web, which relies on ontologies to achieve its goal of making data machine-readable, interoperable, and semantically enriched. Semantic Web's vision is to transform the web into a universal medium where machines can not only access but also interpret, integrate, and reuse data from diverse sources. By embedding semantics (meaning) into data, the Semantic Web facilitates automation, advanced reasoning, and knowledge discovery, enabling systems to provide more intelligent and context-aware services [42].

A key concept closely linked to the Semantic Web is Linked Open Data (LOD), which focuses on publishing and interlinking datasets using web standards such as RDF (Resource Description Framework). LOD enables seamless data sharing and integration across domains, promoting transparency and reusability [43]. Together, the Semantic Web and LOD provide the foundation for creating a globally interconnected web of structured data that can support cross-domain applications, such as semantic search engines, recommendation systems, and decision-making tools.

Ontologies are central to the Semantic Web and Linked Open Data, providing a formal representation of knowledge within specific domains. They define concepts, relationships, and rules that establish a shared understanding of data across systems, ensuring semantic consistency and interoperability. In the context of LOD, ontologies play a critical role by supporting data integration and facilitating complex queries across multiple datasets.

Another vital component of the Semantic Web is Semantic Web rules, expressed through languages such as the Semantic Web Rule Language (SWRL) [44]. These rules enable logical reasoning by defining conditions and relationships between data elements. By combining ontologies and rules, the Semantic Web empowers machines to derive new knowledge, automate tasks, and validate data consistency, further enhancing its intelligent capabilities [45].

Recent advancements have integrated Artificial Intelligence (AI), particularly Machine Learning (ML) and Deep Learning (DL), with Semantic Web technologies. These developments are transforming the scalability and functionality of Semantic Web applications. AI-powered approaches are being used to automate ontology creation, annotate unstructured data, and extract meaningful patterns from vast datasets (Hitzler et al., 2021). For instance, machine learning models can complement ontological reasoning by identifying patterns that would be difficult to encode manually, while deep learning algorithms enhance tasks like natural language processing and image recognition within the Semantic Web ecosystem.

The emerging field of Semantic AI combines symbolic reasoning from the Semantic Web with data-driven AI methods, creating intelligent systems capable of contextual understanding and dynamic adaptation. Applications such as knowledge graph construction, semantic search, and recommendation systems illustrate how Semantic Web principles and AI techniques can work together to deliver powerful solutions. Hybrid models that integrate ontological reasoning and deep learning are opening new avenues for advanced and scalable applications, including autonomous decision-making and predictive analytics. These integrated approaches, where the Semantic Web, ontology, and other cutting-edge fields like AI converge, are increasingly capturing the interest of construction informatics researchers.

For example, Li and Petzold [46] developed an ontology-driven knowledge graph interfacing with advanced large language models (LLMs). This innovation facilitates effective question answering and knowledge retrieval within the domain of additive manufacturing in construction. Similarly, Qiang et al. [47] proposed a framework that leverages AI and Semantic Web technologies to exchange, transmit, and process vast amounts of heterogeneous data from BIM and IoT platforms, significantly enhancing the energy performance of green buildings.

In summary, while still in its early stages, the integration of Semantic Web technologies with emerging fields such as AI is gaining traction. This trend is exemplified by the works of Li and Petzold [46], focusing on ontologies and LLMs, and Qiang et al. (2024), who combined AI and Semantic Web technologies to address energy efficiency challenges.

4. Overview of BIM ontologies

Ontology-based modelling is a widely applicable methodology for knowledge representation across several domains. Farghaly et al. [48], in their synthesis and critical analysis of ontology literature in the Architecture Engineering and Construction domain, summarised the various uses of ontology-based solutions to address various construction industry problems, including smart cities, monitoring and control, safety, process, cost, compliance, operations and maintenance, sustainability, heritage BIM, Industry Foundation Classes among other miscellaneous applications. This section reviews some of these earlier efforts.

In their study, Kreider [49] maintained that the lack of a common language or vocabulary for sharing information with others when implementing BIM is a main barrier. They affirmed that implementing BIM involves several concepts, properties, and other entities, including relationships and having a shared vocabulary for describing them is crucial to achieving a common understanding of BIM. Kreider [49] developed an ontology for BIM uses, drawing from the CIC BIM Protocol and other works. They used a six-step process consisting of ontology definition, scope, knowledge acquisition, documenting concepts, integrating the concepts, evaluation and final documentation. The study also developed an application of the BIM-use ontology. However, Kreider's [49] work did not model the relationship between the uses of BIM even though they presented a structure.

Also, drawing from earlier works, Succar et al. [null] developed an ontology for BIM, self-described as informal and semi-structured, representing a system architecture of BIM concepts, a set of possible relationships and attributes to enable the modelling and analysis of the interactions between the linked entities. Their ontology comprises four high-level classes or knowledge objects, including the main concept (data source, information use, document, format, machine, model use …), attributes (cost, description, location, type …), relations (describe, authorise, assess, control …). While Kreider's [49] work sought to document mainly process-oriented descriptions of BIM uses, Succar (2016) presents a more robust model with the identification of 158 possible relationships (properties) which can be reused in other ontologies. It is essential that BIM ontologies are developed incrementally, more so since interoperability and shared understandings are the main goals of knowledge models.

Lee et al. [50] address the lack of semantic and logical consistency between Information Delivery Manuals (IDMs) and Model View Definitions (MVDs) in the exchange of building information, which leads to vague, inconsistent, and manually defined requirements across domain-specific processes. To overcome this, the authors propose an ontology-based approach to formalize domain knowledge, specifically for the precast concrete domain, and generate consistent, machine-readable IDMs and MVDs by linking them through semantic reasoning and automated translation from OWL/XML to mvdXML using the IfcDoc tool.

Whilst many ontologies have sought to capture broad concepts or entire design and/or construction processes or workflows, Pinzon (2020), in one of the efforts focussed on specific application areas, published a report where they presented BIM family ontologies for materials and components related to Heating, Ventilation, and Air Conditioning (HVAC) equipment used in renovation projects. This is very important work in that it shifts from the focus on new works to renovation works, which are strongly connected to sustainability efforts. They presented three ontological models, including models for installing components in building renovation projects, lifecycle assessment and building energy models. Their project aimed to model complete information about the building renovation knowledge domain. Similarly, the Ontology Engineering Group (2020) on the BIMERR Renovation 4.0 project developed an application-specific ontology model specifically for renovations and energy/utilities-related work. They developed ontologies for, among other things, a building structure, materials, information and the renovation process. The BIM4EEB project, which the RISE Research Institute Sweden is also part of, among other organisations, sought to exploit linked data from renovation projects. They sought to combine existing ontologies with modular ontologies, enhance, harmonise and evaluate them. In another research, Qi and Constin [51] developed an ontology-based framework for the Design for Manufacture and Assembly (DfMA) of prefabricated and modular building elements to address the lack of information interoperability, inefficient data processing and requirements checking.

In one of the new and emerging applications to the administration of payments, a key area of commercial management, Feng et al. [52] developed an ontology to aid information management for subcontractor payment requests by helping to aggregate work done by them, linking that to the information needed to process their payment and generate ledgers.

Chen and Luo [53] addressed the lack of semantic information in IFC-based information exchange within the AEC industry, which they assert hinders its application. They reviewed the current research on ontology development for BIM and proposed an application framework to address the identified problem. In their study, Dris et al. [54] proposed an ontology for combining BIM and virtual reality applications. Their model has the capability to generate object-specific functions and capabilities according to their taxonomy.

Founded on the nonexistence of BIM ontologies that capture the full project life cycle considering the many possible interpretations of BIM and related concepts, Matějka and Tomek [55] proposed a clear difference between research and practice ontologies and also made a distinction between BIM and what they referred to as 'other information models' an earlier term for concepts that have now been more clearly defined in the ISO 19650 (AIM, PIM, etc.).

Getuli's [56] thesis developed an ontology-based BIM expert system for temporal and special construction planning. By identifying and modelling spatial constraints, this study is conceptually like some of the more recent applications of ontologies in transport and city planning research. Their prototype was designed to automate construction scheduling methodologies and is considered an enabler of intelligent systems frameworks for construction spatial planning. In a similar study, Wang and Issa [57] explored the use of ontologies and IFC to solve the problem of pedestrian routing based on indoor geospatial and geographic information systems. Whilst several researchers have developed ontologies in GIS and geospatial data integration with BIM, Usmani et al. [58] examined the complexity of the existing BIM-GIS data format, which typically requires human intervention and may lead to data interoperability issues at the process level.

Cursi et al. [59] examined the potential of enriching BIM representation using the semantic web to 'represent knowledge rather than information'. Schulz et al. [60] introduced a formal ontology, bcfOWL, for BIM collaboration, which converts BIM Collaboration Format (BCF), a buildingSMART standard for communicating issues in BIM models across heterogeneous BIM software into semantic web representation leveraging the expressive capabilities of OWL. Ultimately, they aimed to integrate with the linked building data to enable synergy between heterogeneous building data.

Göbels and Beetz [61] proposed an ontology-based approach that automatically converts the German ASB-ING data model (a German standard for documenting inspection data of bridges and tunnels) into a semantic ontology, thereby transforming legacy infrastructure maintenance data into Linked Data models. This facilitates interoperability, enhanced data accessibility, and integration with other ontologies (e.g., ifcOWL, European Object Type Library), ultimately supporting advanced digital infrastructure management and analysis. Karlapudi et al. [62] developed an ontology-based framework for managing Level of Detail (LOD)-sensitive BIM data, enabling flexible, semantically rich, and interoperable representation and querying of BIM information across different project stages and LOD systems.

Tang et al.'s (2023) study focussed on the limited properties of IFC specification. They employed a natural language understanding methodology for automatically modelling BIM model concepts. Nguyen and Shamak [63] developed an ontology to address the problem of manual, time-consuming and error-prone data entry in simulation-based assessment analysis processes with BIM. They presented a method – ontology generation for geospatial data that enables automatic ontology generation from XSD documents.

Klusmann et al. [64] developed an online platform for semi-automated EIR and BIM EP verification across the project lifecycle. Although the outputs were structured using formats like mvdXML, they did not represent an ontology. Rather, the emphasis was on extracting project-specific requirements, typically presented as checklists and guidelines, which formed the basis for a BIM-based information delivery control tool.

Tchouanguem et al. [8] critically analysed the ifcOWL ontology and the associated BIM interoperability issues. The findings showed how the issues can be resolved using Basic Formal Ontology (ISO/IEC 21838-2) as top-level architecture. Djeudja et al. [5] proposed an approach that can be used to make environmental data available in the early phases of the building lifecycle. It relies on Semantic Web techniques, especially Linked Data principles, while building on emerging BIM technology to propose an approach that facilitates information exchange to enhance the sustainability assessment of buildings.

Hagedorn and König [22] investigated the compatibility of business process modelling and linked building data. Whilst other researchers hitherto had, to some extent, demonstrated or modelled collaborative delivery processes using similar approaches in previous works, the authors extended research in this area by developing an information delivery process ontology evaluated using two cases where XML-based business processes were converted to RDF-based ontology. They drew from previous works, such as by Lee et al. [50], who developed an ontology that addressed the lack of a clear, logical link between the exchange requirements of an information delivery manual based on ISO 29481. Self-admittedly, Hagedorn and König's [22] work demonstrate an approach for linking/aligning business process management and demonstrates only a limited scope of possible applications with the potential to extend it further to capture completed integrated information delivery.

Hagedorn [23] is one of the authors currently seeking to extend and expatiate the linked document delivery protocols for the information container. Hagedorn [23] acknowledges the current understanding of information-sharing mechanisms and media as still dominated by image, document and textual formats, which are impediments to seamlessly linked data from various information sources and domains. Hagedorn's [23] doctoral thesis focused on the semantic validation of information containers and repositories of digitally addressable heterogeneous project information for reliable BIM information exchange. A key outcome of the thesis is the development of an information delivery process ontology (IDPO), which draws from established ontology engineering methodologies to address the four key problems of interest in the thesis: lack of standardised exchange requirements in information containers; lack of clarity on how information containers manage files, particularly regarding ISO 19650 information status (Work In Progress, etc.); insufficient data linking; and lack of automatic validation of the content of the information container. Additionally, the work extends to developing a framework for validating link sets and cross-domain information container contents. These are crucial, considering that the information container is the most critical part of collaborative information creation and exchange following the guidance of standards like ISO 19650.

Farghaly and Jones [65] developed the Sustainable Finance Information Requirement (SFIR) ontology, a formal framework designed to align top-down sustainability policies with material/building data collection. The ontology aims to streamline information flows between buildings and financiers, thereby enhancing stakeholder coordination and promoting sustainable development in the built environment. Also, Farghaly et al. [66] developed a novel approach to integrating BIM and Geographic Information Systems (GIS) using semantic web technologies, facilitating enhanced data interoperability and supporting more effective urban planning and management decision-making.

As the foregoing suggests, many researchers have explored various applications of ontology development in the BIM domain. Notably, Fargharly et al. [48] weighed the merits of large vs small ontologies and new vs extended ontologies. They ultimately argue for smaller ontologies and more extensions of existing ontologies. These are reasonable arguments. However, most of the studies reviewed in this section rarely reference ISO 19650, which is understandable given that much of the research predates its publication. For instance, Kreider's ontology (2013) and Succar's framework (2009, 2016), discussed in the preceding sections, were developed before ISO 19650 was introduced. Despite the advancements in this area of research in the last few years and growing research interest in the area [48], there remains a need for models that effectively connect BIM standards with their interrelationships, reinforcing the need for continued development in this area. Building on these foundational works, the proposed BIM-OIM advances the field by holistically integrating ISO 19650 standards, formalising knowledge representation, and establishing machine-readable links between key BIM concepts to enhance interoperability.

5. Research methodology

This study is informed by the philosophical position of pragmatism, which draws from both objective and subjective worldviews [67]. A pragmatic paradigm is problem-focused and seeks practical solutions, often using mixed- or multi-methods, recognising the value of quantitative and qualitative data. Pragmatism emphasises practicality and utility in generating knowledge. In the context of ontology development, a pragmatic approach focuses on the usefulness and effectiveness of the ontology for specific purposes. For BIM-OIM to be adopted by other researchers and professionals, it has to be useful and effective from a practice perspective. Thus, empirical evidence about the objectiveness, reliability of quantifiable data and the ease of interpretation of the information embedded in BIM-OIM is imperative.

Over the years, different ontology development methodologies have emerged. Some include: Methontology, On-ToKnowledge, NeON, Melting Point, OntoSpec, DiDOn, and TDDonto, "Ontology Development 101", Gruninger & Fox, Uschold and King Methodology, Distributed Engineering of Ontologies (DILIGENT), Toronto Virtual Enterprise (TOVE), Unified Process for Ontology (UPON), YAMO [68], RapidOWL Methodologies. Given the data-intensive and complex nature of the BIM information management domain and related standards, YAMO is the most appropriate as it allows for the development of large-scale ontologies. YAMO emphasises large-scale and faceted ontology construction, addressing complexity and extensive data representation needs.

YAMO contains a 9-step approach, as indicated in the framework of Fig. 1.

Duplicating the efforts to define the steps in the YAMO methodology will add no value to this work. Therefore, researchers interested in furthering their understanding of the details of each step can consult the developers [68]. The ensuing sections will examine the operationalisation of the steps for developing BIM-OIM.

6. Development of BIM-OIM ontology

Domain Identification: In this step, the specific domain from a vast universe of knowledge is identified. The user requirements, application needs and goals of the proposed ontology inform the identification of the domain of interest. One of the main goals of BIM-OIM is to serve as a knowledge base where end-users can gain knowledge about the implementation of ISO 19650 in managing information during the lifecycle of projects. Also, it could be about identifying and learning from BIM-compliant projects.

Domain Footprint: The domain footprint examines the purpose and application of the intended ontology in a specific scenario. The data-information-intensive and complex nature of the information management process is compounded by the need to align with standards such as ISO 19650, and many scenarios have been envisaged. The BIM-OIM ontology serves as a structured knowledge base

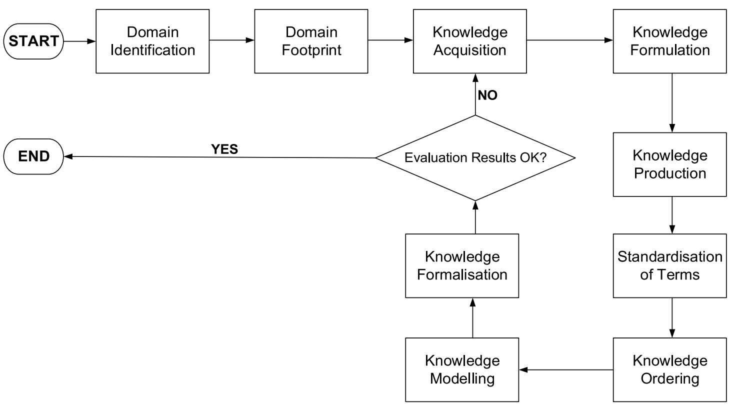

Fig. 1. General framework of YAMO (Adapted from Ref. [68]).

that enables professionals to develop and implement BIM Execution Plans (BEPs) more effectively. By leveraging machine-readable, ontology-driven processes, BIM-OIM ensures that critical BEP components align with ISO 19650 standards and industry best practices. This structured approach enhances collaboration, improves data consistency, and streamlines information management workflows across project lifecycles.

Key elements of a BEP that BIM-OIM supports include the Master Information Delivery Plan (MIDP) for coordinating information exchange, Exchange Information Requirements (EIR) for defining project-specific data needs, and Information Containers for structuring and managing digital assets. Additionally, BIM-OIM ensures standardization of file types and formats, improving interoperability across different software platforms. It also integrates technologies such as Common Data Environments (CDEs), facilitating secure, collaborative, and efficient data exchange. By embedding these elements, BIM-OIM enhances the automation, validation, and compliance of BEPs, making information management more structured and reliable.

Knowledge Acquisition: An extensive knowledge acquisition process was conducted to identify different terms relevant to the domain for which the ontology is built. A list of terms relevant to the domain is collected from different literature sources, including standards, guidelines and PhD thesis. The first criterion for this choice focused on relevance to BIM standards and ontologies. Priority was given to internationally recognized BIM standards such as ISO 19650, as well as industry guidelines that define structured methodologies for BIM information management. To maintain credibility and scholarly rigour, only peer-reviewed journal articles, conference proceedings, and PhD theses were considered. Literature published in high-impact journals and reputable research institutions was prioritized to guarantee that the selected sources reflect accurate, validated, and well-researched knowledge. Another key factor in the selection process was the coverage of core BIM concepts and information management processes. Studies addressing BIM information exchange frameworks, such as BIM Execution Plans (BEPs), Exchange Information Requirements (EIRs), and validation of information containers, were specifically targeted.

With regards to standards, the focus was on ISO 19650, the recommended standards for delivering BIM-compliant projects. The guidelines were obtained from the UK BIM Framework, an initiative supported by BSI, CDBB and the UK BIM Alliance, whose goal is to drive the implementation of BIM in the UK (UK BIM, 2023), BIMe Initiative – an initiative aimed at organising knowledge in a structured format that can be read by humans as well as machines (BIM I., 2015). A PhD thesis by Akintola [69] investigated how organisational and project team practices coevolve with the implementation of BIM. Although the thesis focused on the PAS 1192 suite of standards, it provided some principles that informed learning from ISO 19650.

Following one of the principles of ontology development, certain concepts from the Digital Construction Ontologies (Törmä and Zheng, 2020) were re-used. Specifically, the Agent concept was re-used to reinforce the principle of interoperability. It was also defined as an equivalent class to (EquivalentTo) the Actor class. The Actor class together with some of its concepts such as Person, Organisation including sub-classes and properties such as isResponsibleFor were elicited from the digital construction ontologies (Törmä and Zheng, 2021). The Ontology of Geographical Regions [70] was re-used. Also, some concepts were re-used from the BIMe Initiative; for example, “Collaborate with (collboratesWith) and Communicate with (communicatesWith) [71] were re-used.

Besides the aforementioned references, various knowledge resources were considered to gain a clear insight into the domain. BIMERR [72] and BIM4EED [73] are a few such sources. Other built environment semantic web applications research (e.g., Ref. [13,14,38]; [null], [14,18,37,74]) and BIM related ISO 19650 studies (e.g., Ajayi and Oyebiyi [75]) were reviewed.

The decision to reuse concepts from existing ontologies is based on three key justifications. First, it aligns with a fundamental ontology development principle, which advocates leveraging established domain-specific concepts to avoid unnecessary duplication. Second, reusing existing concepts enhances interoperability and supports best practices in ontology engineering, ensuring a structured and coherent representation of BIM-related knowledge. Lastly, incorporating concepts from diverse sources enriches the BIM-OIM, providing a broader and more comprehensive perspective.

Knowledge Formulation: Knowledge formulation is the process of organising, structuring, and representing information or expertise systematically and structured. It involves transforming raw knowledge into a formalised, understandable, and often standardised format. The terms collected in the knowledge acquisition phase are analysed and structured or organised based on the

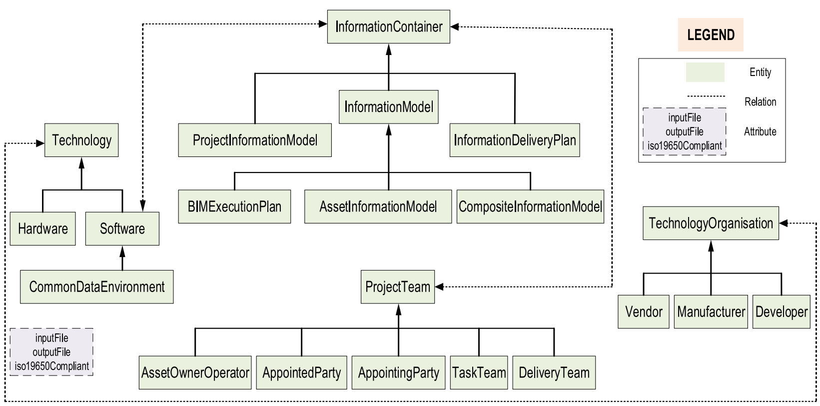

Fig. 2. Snapshot of the BIM-OIM ontology.

scope and coverage of the principal concepts about the information management process in alignment with ISO 19650. The principles guiding this process are relevance, the principle of permanence, the principle of exclusiveness, the principle of exhaustiveness, the principle of ascertainability, the principle of consistency, and the *principle of context* (Ranganathan, 1967). The analysis is done based on the definitions of the identified terms, their characteristics, and their appropriateness in the information management process. Apart from exhaustiveness, all other guiding principles align with the development of BIM-OIM, which is underpinned by the well-structured ISO 19650 document. To ensure BIM-OIM is exhaustive, additional concepts such as Project, Actors, and Technology were explicitly included in the ontology hierarchy. This inclusion addresses the fact that while these concepts are implied in ISO 19650, they are not explicitly represented, potentially limiting the standard's clarity and understanding.

Knowledge Production: Knowledge production involves the creation, development, and structuring of formal representations of knowledge within a specific domain. This process includes defining concepts, relationships, properties, and axioms in a formal ontology. The aim is to capture and organise knowledge in a structured and standardised way to enable effective information retrieval, reasoning, and sharing. A top-down approach is used to organise concepts, relationships and properties in a format easily understood by end-users and implemented in a software environment. The DERA (Domain, Entity, Relation, Attribute) faceted knowledge organisation framework will be used. DERA organises knowledge into facets by defining any number of domains. An excerpt of the BIM-OIM in DERA is presented in Fig. 2.

By utilising the DERA framework to represent BIM-OIM knowledge, it not only enhances visualization and comprehension but also supports software specification, design, construction, and maintenance.

Standardisation and Ordering: The term standardisation is the process of developing a consistent and uniform set of terms and definitions that can be universally understood and utilised within a specific field or across various fields. Recognising that each concept can be represented by multiple synonymous terms, this process involves choosing a preferred term from among these synonyms when multiple options are available. For example, BIM Stage 2 and BIM Compliant project are synonyms. In this instance, BIM Stage 2 is selected as the preferred term because BIM Stage 2 is part of the BIM maturity model defined in ISO 19650. However, given the need to further widen and enhance understanding, an equivalent class concept was used to relate BIM Stage 2 and BIM Compliant project instead of dropping the later.

Knowledge Modelling and Formalisation: Knowledge modelling involves structuring and modelling the various facets of domain knowledge. It depicts the entity, entity relationships and their properties unambiguously, and allows preservation of knowledge, which further ensures the aggregation, substitution, improvement, sharing and reapplication of the ontology.

To illustrate the knowledge modelling task, excerpts of the "Process" concept will be used to illustrate how the sub-classes were structured. This is depicted in Fig. 3.

In the literature, most developed ontologies are structured without numbering, as illustrated on the left side of Fig. 3. Examples of such approaches can be found in Tah and Abanda [38], Abanda et al. [null], and Abanda et al. [null], where classes are included in the hierarchy without a specific order. However, since this study focuses on BIM, particularly Information Management, the logical sequence of information flow is crucial. To indicate this flow direction, which aligns with the concept of "workflow" commonly used in the BIM community, the classes on the left are numbered. This numbering ensures a structured order and aligns with ISO 19650, thereby enhancing clarity and ensuring that all relevant concepts from the standard are properly integrated.

The structure of the concepts in BIM-OIM was heavily informed by the way how concepts are displayed when represented in Protégé-OWL. When concepts are edited into Protégé-OWL, they are displayed in alphabetical order, which may not necessarily follow the obvious ISO 19650 workflow. As indicated on the left screenshot of Fig. 3, the "Process" concept has sub-concepts that are not organised nor align with the ISO 19650 workflow. On re-organising/structuring by numbering the high-level and sub-concepts, the output is as displayed on the right of Fig. 3. This is now clearer and aligns with ISO 19650.

Knowledge formalisation is the process of converting knowledge into a structured and explicit format that can be easily represented, shared, and utilised. It involves translating information, experiences, or expertise into a standardised form that can be

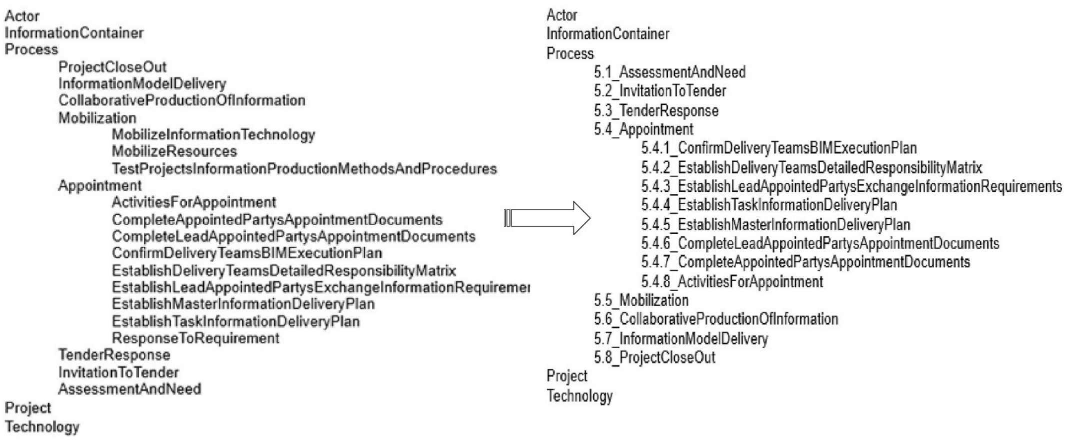

Fig. 3. An excerpt of the "Process" concept in the BIM-OIM ontology.

understood and used by computer systems or individuals. This formalisation typically includes defining concepts, relationships, rules, and other elements that make up the knowledge domain.

As discussed in Giunchiglia et al. (2014), the Description Logics (DL) formalisation of any DERA domain is a direct encoding from the DERA facets into DL formulas. The DL formalisation of DERA domain is done by modelling its components, such as entity, relation, and attribute, as DL concepts, roles, and individuals, as shown in the DL formalisation Table 1.

In Table 1, entity classes, representing a set of entities, are formalised as DL concepts, entity instances are formalised as DL individuals, relations and attributes are formalised as DL roles.

Evaluation: The ontology evaluation task follows the formalisation of the ontology. This task involves assessing the technical health of BIM-OIM and determining whether it fulfils its intended purpose. Due to the technical rigour and challenges associated with evaluating ontologies, which necessitates the use of the Protégé-OWL tool, Section 9 is dedicated to this crucial task.

7. Implementation in software environments

7.1. System architecture

To establish the context for the system architecture, it is essential to reaffirm and justify the nature of BIM-OIM. We selected a domain ontology because it formalizes concepts from ISO 19650, specifically for BIM information management, ensuring relevance to the construction sector rather than a broader or unrelated domain. Additionally, we opted for a formal ontology based on description logic, structured using OWL (Web Ontology Language). This approach enables machine-readable reasoning, consistency checking, and automated inference, enhancing interoperability and ensuring compliance with industry standards. The system architecture, as illustrated in Fig. 4, is designed to represent BIM-OIM and facilitate these capabilities, ensuring seamless integration into digital workflows.

This study used Protégé-OWL, reasoners (ELK and HermiT) and SWRLTab. Protégé-OWL is a rich ontology editing environment with full support for the OWL 2 Web Ontology Language and direct in-memory connections to description logic reasoners like HermiT and ELK. In this manuscript, Protégé-OWL is utilised as a tool for creating and managing ontologies, while OWL serves as the encoding language used to formally represent the ontologies developed using tools like Protégé-OWL. Protégé-OWL 5.6.3 was the main version used for modelling the different concepts. The reasoners HermiT and ELK were regularly used in checking technical consistencies. The Semantic Query-Enhanced Web Rule Language (SQWRL) is a query language built on top of SWRL that offers SQL-like operators to extract information from OWL ontologies. Essentially, while SWRL allows for the creation of rules to infer knowledge, SQWRL is used to query that knowledge and retrieve information based on the rules defined in SWRL. SWRLTab is a plugin in Protégé-OWL that was used to create BIM-OIM rules.

Table 1
Formalisation of BIM-OIM into DL.

	BIM-OIM domain elements	DL formalisation	Examples	
$E_1, \ldots \ldots E_n$	Entity classes	Concept	InformationModel, Project, TaskTeam, AppointingParty	TBox
$R_1 \ldots \ldots R_n$	Relation between classes	Roles	isAppointedBy(AppointingParty, LeadAppointedParty), submitsTo (TaskTeam, LeadAppointedParty)	
$A_1 \ldots \ldots, .., A_n$	Attributes	Roles	hasStatusCode(InformationModel, Status), hasFileType (InformationContainer, FileType)	
is-a	Hierarchical relation	Supsumption	TaskTeam ⊑ Actor, AppointingParty ⊑ Organization (meaning TaskTeam is a subclass of Actor)	
part-of	Hierarchical relation	Roles	isPartOf(InformationContainer, CommonDataEnvironment), isPartOf (TaskTeam, DeliveryTeam)	
Any relations that are non-hierarchical type	Associative relations	Roles	collaboratesWith(LeadAppointedParty, TaskTeam), communicatesWith(ProjectManager, Contractor)	
Value-of	Hierarchical relation	Role restriction	hasLevelOfInformationNeed(InformationModel, LevelOfDetail) where LevelOfDetail has predefined values (LOD 100, LOD 200, LOD 300)	
$e_1, \ldots e_n$	*Entity instances*	Individuals	Crossrail_Project: Project, Royal_Adelaide_Hospital: Project	ABox
$r_1, \ldots, r_n$	*Relation between entities*	Role assertions	submitsTo(TaskTeam_X, LeadAppointedParty_Y), meaning TaskTeam_X submits work to LeadAppointedParty_Y	
$a_1, \ldots a_v$	*Attribute of entities*	Role assertions	hasFileType(InformationContainer_X, "IFC"), hasStatusCode (InformationModel_Y, "S1″)	
$v_1, \ldots v_t$	*Attribute values*	Individuals	"S1" (for Status), "RVT" (for FileType), "1234" (for ProjectCode)	
instance-of	Hierarchical relation (between entity classes and entity instances)	Concept assertions	Crossrail_Project: Project, meaning Crossrail_Project is an instance of the Project class	

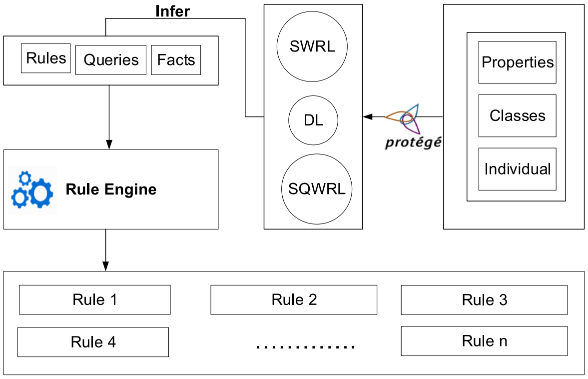

Fig. 4. System architecture.

7.2. BIM-OIM concepts

7.2.1. BIM-OIM classes and instances

The classes in the BIM-OIM ontology were generated in 3 different ways. The first category classes were abstracted (re-used) from existing ontologies, e.g., Actor. The second category group of classes was developed from scratch and abstracted from BIM standards, e.g., DeliveryTeam, TaskTeam, AppointedParty, InformationContainer, etc. The abstraction process was carried out through manual examination of ISO 19650 Parts 1 and 2. For instance, the concept of the InformationContainer appears repeatedly throughout these standards, including explicit references such as in Clause 5.1.7, part (e). The main classes of BIM-OIM have been captured in Fig. 5.

The third category of classes were obtained "Equivalent" classes, as defined in the Ontology development guide by DeBellies (2021). The concept of "equivalent" classes, depicted in Fig. 6 will be further discussed in the ensuing paragraph.

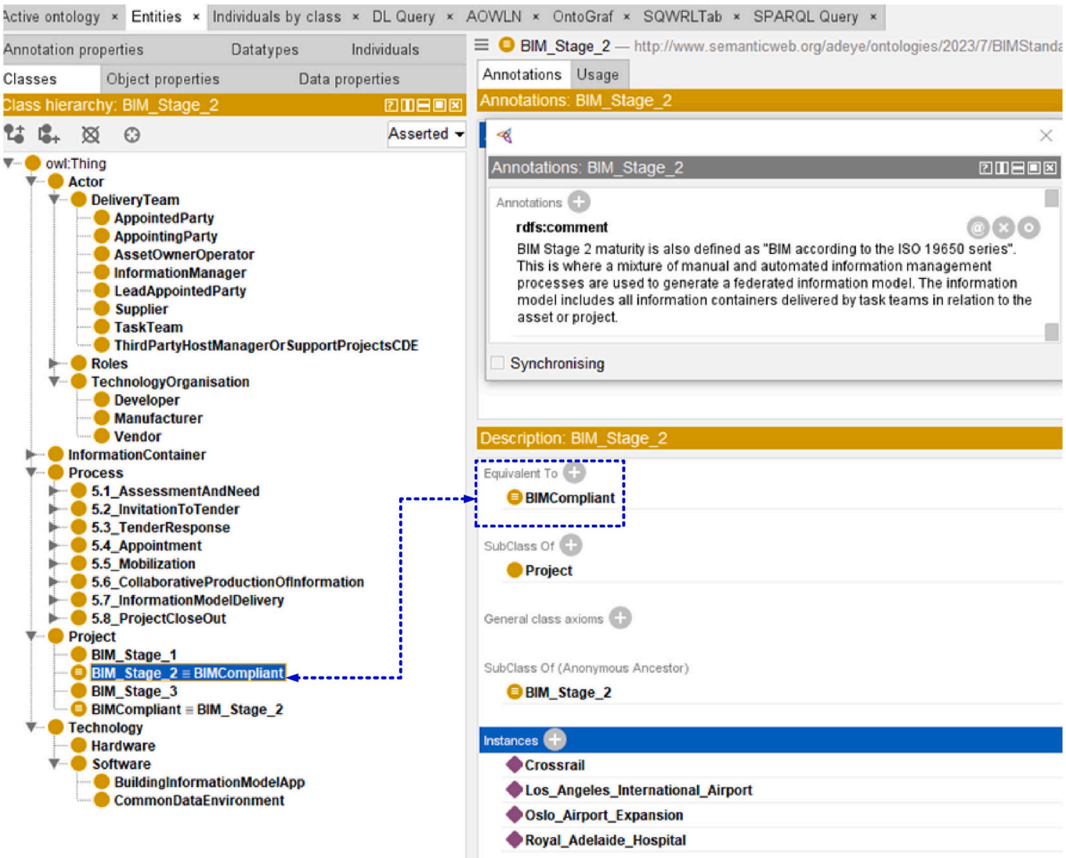

Fig. 5. Classes in BIM-OIM ontology.

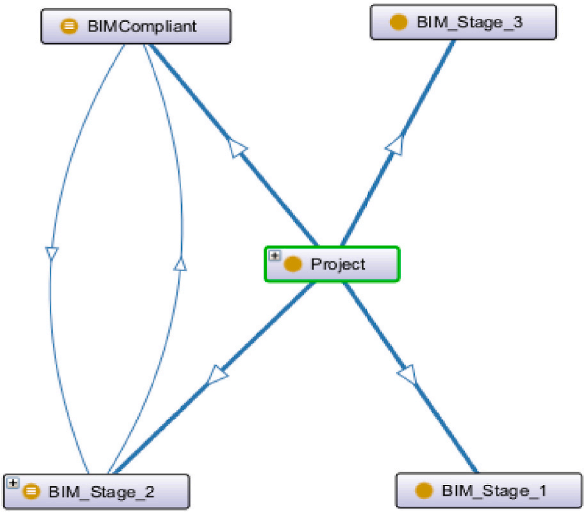

Fig. 6. An example of an equivalent classes in BIM-OIM Ontology.

Class A *EquivalentTo* Class B means that there is an equivalent relation between Class A and Class B. For example, “BIM_Stage 2 is *EquivalentTo* (BIMCompliant)”: “A BIMCompliant project is BIM_Stage 2 project”, and then “A BIM_Stage 2 project is a BIMCompliant project” or “BIM in accordance with BS EN ISO 19650”.

In general, an equivalent relationship a bi-directional relationship that satisfies the following conditions.

- ∀ a ∈ A, a ∈ B: any instance ‘a’ of Class A is the instance of Class B
- ∀ b ∈ B, b ∈ A: any instance ‘b’ of Class B is the instance of Class A

In ontology development, instances, also referred to as individuals, such as *a* and *b,* represent the real-world entities or specific examples that belong to the abstract classes defined within the ontology. These instances are created and assigned to their corresponding classes to accurately model real-life scenarios and data. In the case of BIM-OIM, several real-world projects have been modelled as instances, including Crossrail, Los Angeles International Airport, Oslo Airport Expansion, and the Royal Adelaide Hospital. Thanks to the extensible nature of Protégé, there is no practical limitation on the number of instances that can be created within the system. Protégé enables the continuous expansion of the ontology by allowing users to define new instances as needed, regardless of

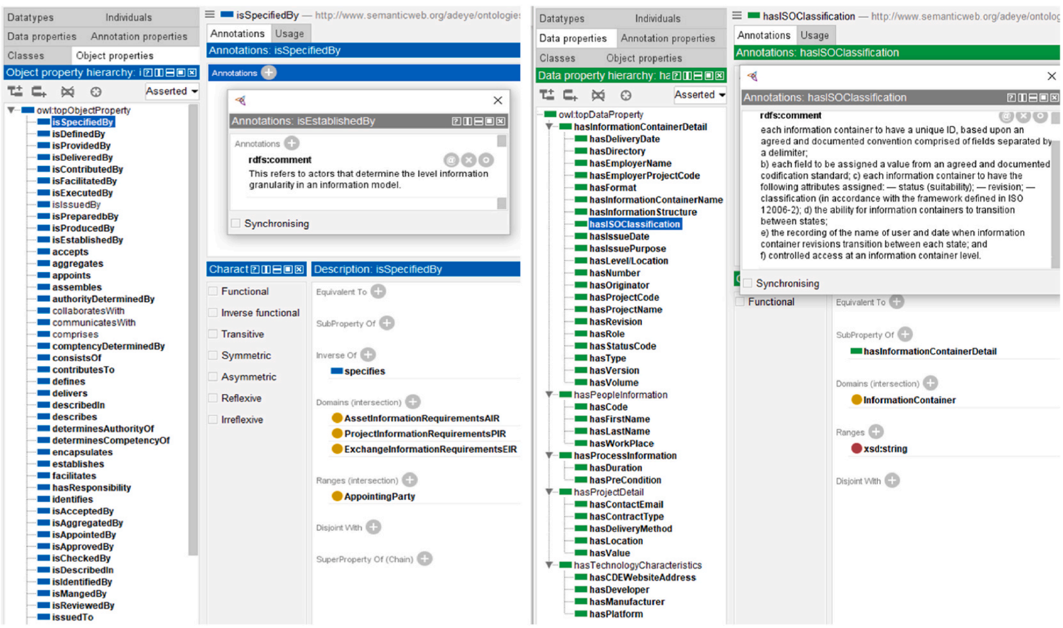

Fig. 7. Object and data properties.

project size or complexity. For example, PRJ987-PQRS-04-LD-XX-SPE-0450-C is an instance representing an information container class within the ontology, illustrating how specific project artefacts can be incorporated seamlessly into the BIM-OIM structure.

7.2.2. Object relationships and data properties

An excerpt of object and data type properties of BIM-OIM have been presented Fig. 7.

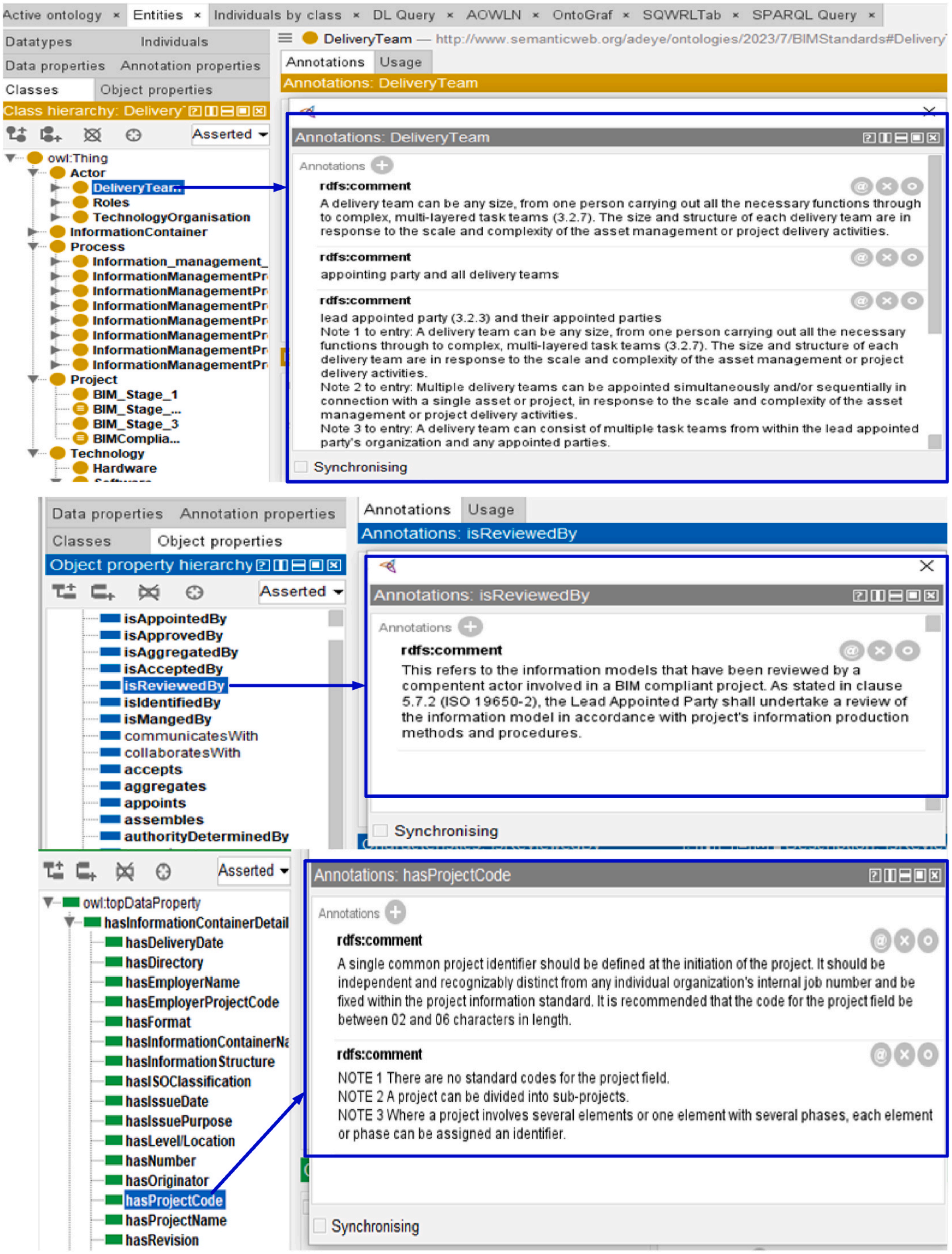

Fig. 8. BIM-OIM annotation properties.

7.2.3. Annotation properties

In ontology engineering, annotations are crucial for adding supplementary information to the elements within the ontology. They can aid in the following.

- Documentation: Annotations are used to document the ontology so that humans can understand it better. This includes explanations, comments, and notes about classes, properties, and other elements.
- Metadata: They provide metadata, which can be crucial for understanding the context, source, or nature of the data.

Some examples of annotation properties have been included in Fig. 8.

7.2.4. Constraints (name of files (information container))

The practice of BIM methods and concepts requires certain constraints to be met to deliver a BIM-compliant project. The constraints may be invoked to ensure effective information management. For example, every BIM Execution Plan is customised to fit the specific needs and objectives of the associated project. The plan may vary in its components, level of detail, and methodologies based on factors such as project size, complexity, contractual agreements, and stakeholder expectations. It is crucial for the BEP to align with the project's unique characteristics to effectively guide the project team in leveraging BIM for successful project outcomes.in other words, every BIM EP is unique. Similarly, the names of every information container are unique. According to ISO 19650, there are certain constraints on naming files.

For example, an information container is unique and named as per recommendation of ISO 19650. For example, an information container could be name as "SC1-SFT-V1-01-M3-A-30_10_30-0001-S1-P02".

The question is, how is the uniqueness of information containers modelled in Protégé-OWL?

This can be represented in protégé-OWL using the DifferentIndividuals axiom to make sure no two information containers can have the same file name. The DifferentIndividuals axiom can be used to explicitly state that multiple instances are distinct from each other. This is a direct way to declare the uniqueness of an instance by listing it alongside other instances from which it is different. This will be illustrated in Fig. 9. If two or more individuals (instances), such as IC1, IC2, …IC9, need to be asserted as unique entities, the DifferentIndividuals axiom should be used to explicitly declare their distinction. As in Fig. 9, IC7 information container is: PRJ987-PQRS-04-LD-XX-SPE-0450-C; this is different for all other information containers of the instances IC1-IC6 and IC8-IC9.

The DifferentIndividuals axiom is among the OWL axioms (e.g., disjoint classes, universal restrictions) used to define constraints within BIM-OIM, complementing SWRL, which operates under an Open-World Assumption (OWA). In contrast to the Closed-World Assumption (CWA), where any missing information is assumed to be false, OWA does not make such an assumption, which can present challenges in BIM environments that require explicit constraints. For example, the DifferentIndividuals axiom ensures that no two information containers share the same unique identifier, thereby reinforcing CWA-like validation, which is essential for

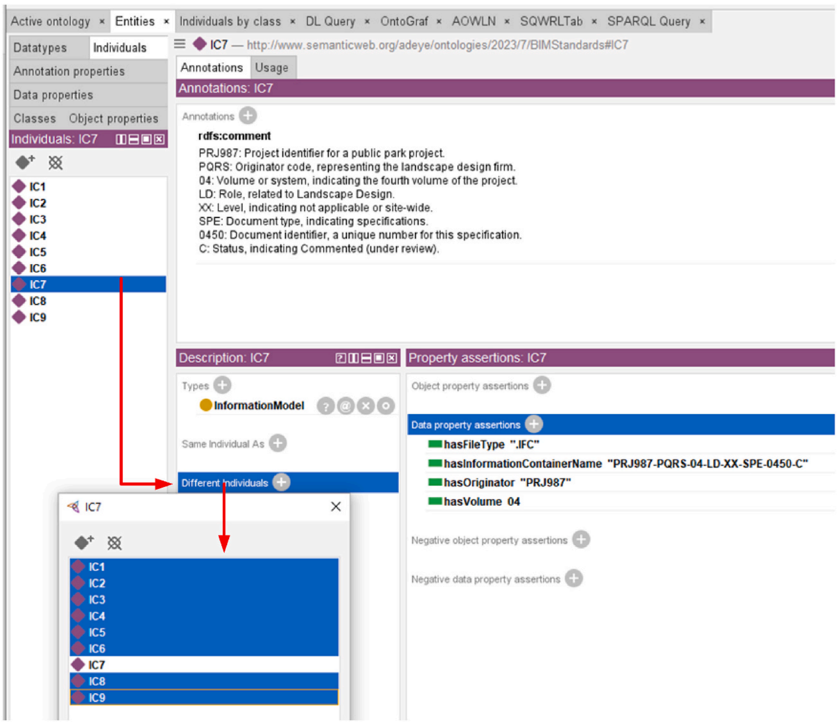

Fig. 9. Constraints in BIM-OIM

maintaining data consistency and integrity in BIM information management.

7.3. Modelling rules in BIM-OIM

A semantic reasoning engine (otherwise known as a semantic reasoner, inference engine, or rules engine) is a piece of software designed to perform reasoning - to apply rules to a data set and conduct semantic inference.

The SWRL represents a sophisticated rule language based on Web Ontology Language (OWL), characterised by its capability to formulate rules akin to Horn clauses, utilising OWL's conceptual framework. This integration enhances deductive reasoning beyond what is achievable with OWL alone. Inherently, SWRL is founded upon description logics, like OWL, thereby ensuring robust formal integrity in inferential processes. SWRL's adherence to description logics imparts unique attributes to rule-based systems developed under its framework. Notably, SWRL conforms to the open-world assumption of OWL, which presents challenges in implementing rules predicated on a closed-world view. Moreover, SWRL maintains a monotonic inference approach, where once deductions are made, they cannot be altered or withdrawn. These intrinsic formal qualities significantly shape the construction and implementation of SWRL rules within ontology-centric applications.

Forward chaining, alternatively referred to as forward deduction or forward reasoning, represents a sophisticated methodology employed within inference engines. This algorithmic approach initiates from a foundation of established facts, systematically activating rules whose initial conditions are met and subsequently integrating their conclusions into the existing factual framework. This iterative process persists until the resolution of the presented problem is attained. Within the realm of forward chaining, the inference engine commences its operation by methodically analysing extant facts, derivations, and conditions. This comprehensive evaluation culminates in the generation of new insights or knowledge. The ultimate objective of this process is realised through a strategic manipulation and application of the knowledge reservoir contained within the knowledge base. The concept of forward chaining is represented in Fig. 10.

A practical example of forward chaining reasoning in BIM-OIM is represented by rules r-1 and r-2.

TaskTeam(?TT) ˆ LeadAppointedParty(?LAP) ˆ submitsTo(?TT, ?LAP) ˆ InformationModel(?IM) ˆ reviews(?LAP, ?IM) - > ReviewAndAcceptInformationModel(?IM) (r-1)

ReviewAndAcceptInformationModel(?IM) - > sqwrl:select(?IM) (r-2)

The interpretation of r-1 and r-2 are as follows.

7.3.1. Explanation of rule r-2

7.3.1.1. Premise (antecedent).

- TaskTeam(?TT): There is a task team, denoted as ?TT.
- LeadAppointedParty(?LAP): There is a lead appointed party, denoted as ?LAP.
- submitsTo(?TT, ?LAP): The task team (?TT) submits something to the lead appointed party (?LAP).
- InformationModel(?IM): There is an information model, denoted as ?IM.
- reviews(?LAP, ?IM): The lead appointed party (?LAP) reviews the information model (?IM).

7.3.1.2. Conclusion (consequent).

- ReviewAndAcceptInformationModel(?IM): If all the above (antecedent) conditions are met, then the information model (?IM) should be reviewed and accepted.

In essence, this rule states that if a task team submits an information model to a lead appointed party and the lead appointed party reviews it, then the information model should be considered as reviewed and accepted or rejected. This is a key task in the information management process as outlined in Clause 5.7 of ISO 19650, which is represented in BIM-OIM as 5.7 in Fig. 5. Likewise, all subsequent

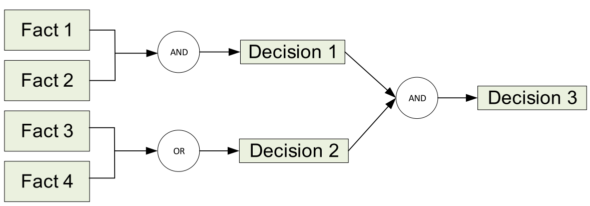

Fig. 10. Concept of forward chaining.

rules are grounded in the requirements of ISO 19650, ensuring alignment with its standards and best practices.

7.3.2. Explanation of rule r-2

7.3.2.1. Premise (antecedent).

- ReviewAndAcceptInformationModel(?IM): An information model (?IM) has been reviewed and accepted.

7.3.2.2. Action (consequent).

- sqwrl:select(?IM): Select or retrieve the information model (?IM) that has been reviewed and accepted.

With regards to the forward chaining concepts in Fig. 10, the facts and decisions in rule r-1 and r-2 are examined in the ensuing paragraphs.

Facts: These are the basic assertions or known truths in the rule-based system. Based on rules r-1 and r-2, the facts are represented by the individual conditions before the implication arrow (->).

- TaskTeam(?TT): There exists a task team, denoted as ?TT.
- LeadAppointedParty(?LAP): There exists a lead appointed party, denoted as ?LAP.
- submitsTo(?TT, ?LAP): The task team ?TT submits something to the lead appointed party ?LAP.
- InformationModel(?IM): There exists an information model, denoted as ?IM.
- reviews(?LAP, ?IM): The lead appointed party ?LAP reviews the information model ?IM.

Decisions: Decisions are the conclusions or actions taken when certain conditions (facts) are met. They are what follow after the implication arrow in a rule.

- **First Rule Decision** (ReviewAndAcceptInformationModel(?IM))**:**
  - o This decision occurs if all the preceding facts in the first rule are true. It implies that the information model ?IM should be reviewed and accepted.
  - o This decision acts as a new fact in the context of the second rule.
- **Second Rule Decision** (sqwrl:select(?IM))**:**
  - o This decision is based on the fact ReviewAndAcceptInformationModel(?IM) from the first rule. If the information model ?IM has been reviewed and accepted, it is then selected or retrieved (as indicated by sqwrl:select(?IM)).
  - o This action represents the output or final step of the logic dictated by r-2.

8. BIM-OIM applications

Like any other ontology, BIM-OIM is an extensible knowledge framework designed to capture and represent information about construction projects. For the purposes of this study, only projects delivered using BIM have been included. The selected projects are Crossrail, Los Angeles International Airport, Oslo Airport Expansion, and Royal Adelaide Hospital (see Fig. 5). These projects are represented as instances/individuals within BIM-OIM, along with detailed information about their properties (object, data, and annotation) being captured.

This approach ensures that the same processes and analyses applied to one project, such as Crossrail, can similarly be applied to any other project within the framework, provided it is represented as an individual and its corresponding information is properly captured. Therefore, referring to Crossrail as a "case study" may be misleading, as the same methodology applies equally to other projects like Los Angeles International Airport, Oslo Airport Expansion, and Royal Adelaide Hospital, all of which are represented within BIM-OIM.

While the queries and rules developed earlier (r-1, r-2) and later (r-3 to r-19) are universally applicable to all instances or individuals (projects) within BIM-OIM, our discussion will focus specifically on Crossrail. This focus is justified by the fact that Crossrail is one of the largest and earliest projects in Europe to adopt BIM [76,77]. Additionally, the information incorporated into BIM-OIM for the Crossrail instance was abstracted and edited from three publicly available sources: Taylor [76,77] and Crossrail Ltd [78]. These publicly accessible documents ensure transparency, facilitate verification, and enhance understanding for anyone interested in exploring the functionalities of BIM-OIM.

The subsequent paragraphs will delve into the specific use case of Crossrail, illustrating its application within the BIM-OIM framework.

8.1. Use case 1 calling out simple data about various parts of the ontology

A common task in Information Management is the determination of Status Codes. A Status Code" refers to a code or label used to indicate the state or status of an information container or document at a particular point in time. A query to call or identify status codes is:

InformationContainer(?IM) ˆ hasStatusCode(?IM, ?SC) - > sqwrl:select(?IM, ?SC) (r-3)

The output of this is a list of status codes of the different information containers.

The query q-1 can be extended to generate in addition to the status code other data such as the file type and the originator of the information container. This is modelled in query r-4.

InformationContainer(?IM) ˆ hasStatusCode(?IM, ?SC)ˆ hasFileType(?IM, ?FT)ˆhasOriginator(?IM, ?OT)- > sqwrl:select(?IM, ?SC, ?FT, ?OT) (r-4)

8.2. *Use case 2 grouping data/information*

Project(?p) ˆ isDeliveredBy(?p, ?c) ˆ sqwrl:groupBy(?p, ?c) - > sqwrl:select(?p, ?c) (r-5)

8.2.1. *Premise (antecedent)*

Project(?p): This part of the rule is a predicate indicating that ?p is a project.

isDeliveredBy(?p, ?c): This predicate specifies a relationship between ?p (a project) and ?c (presumably a contractor or company). It indicates that the project ?p is delivered by the entity ?c.

sqwrl:groupBy(?p, ?c): In SQWRL, a query language built on top of SWRL, groupBy is used to aggregate results based on certain properties. Here, it suggests an intention to group the results by projects and their delivering entities, though groupBy is not a standard SWRL built-in and seems to be used here in a SQWRL-like context. Typically, groupBy is part of SQL or similar query languages, and its use here implies aggregating or organising query results based on projects and their deliverers.

8.2.2. *Action (consequent)*

sqwrl:select(?p, ?c): This indicates the result of the rule or query, where select is used in SQWRL to specify the data to be returned from the query. In this context, it means that for all projects and their associated delivering entities that meet the criteria of the first two conditions (being a project and being delivered by an entity), those pairs of projects and entities should be selected and returned as results.

8.3. *Use case 3 pulling out information containers*

In the UK, the unique ID for information containers within a CDE should be defined using the following fields, separated by a delimiter in accordance with the following convention.

The rules governing the number of and type of characters of the aforementioned fields can be obtained from BE ISO 19650–2:2018, National Annex NA. An example of unque ID is: 6025-BBH-ZZ-03-DR-B-00023.

InformationContainer(?IM) ˆhasProjectCode(?IM, ?a) ˆhasVolume(?IM, ?b) ˆhasLocation(?IM, ?c) ˆhasRole(?IM, ?d) ˆhasType(?IM, ?e) ˆhasNumber(?IM, ?f) ˆswrlb:stringConcat(?k, ?a, ?b, ?c, ?d, ?e, ?f)- > hasInformationContainerName(?IM,?k) (r-6)

hasInformationContainerName(?IM,?k) - > sqwrl:select(?IM, ?k) (r-7)

This rule (r-7) is used to query for and return all instances of Information Models (?IM) along with their associated Container Names (?k).

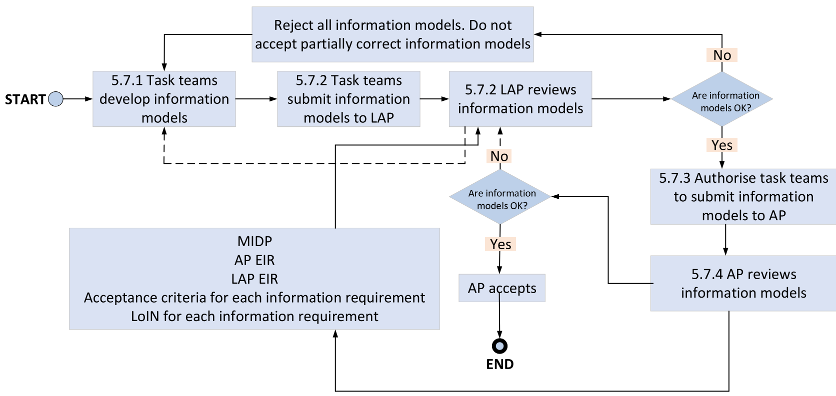

Fig. 11. Process map of information model delivery.

8.4. Use case 4 information model delivery

The Information Model Delivery phase of information management lifecycle, as defined in Clause 5.7 of ISO 19650, is a critical stage in the lifecycle of BIM project. This is because it is the phase in which information is handed over to the appointing party.

The full meanings of the terms in Fig. 11 are: MIDP (Master Information Delivery Plan), AP EIR (Appointed Party Exchange Information Requirement), LAP EIR (Lead Appointed Party Exchange Information Requirement) and LoIN (Level of Information Need; please note that LoIN is not a standard representation. It is just an abbreviation as used in Fig. 11). Based on Fig. 11, the first 3 steps of the information model process correspond to clauses 5.7.1 and 5.7.2 of the ISO 19650–2:2018 standard. The most important activity in the first three steps of Fig. 10 or clauses 5.7.1 and 5.7.2 is the "Review and Authorise the Information Model", which will be examined in the ensuing paragraphs, i.e., use case 4-a.

Use case 4-a Review and authorise the information model (by the LAP)

According to ISO 19650–2:2018, in reviewing before deciding whether to authorise or reject models from task teams, the LAP shall consider deliverables in MIDP, LAP's EIR, AP EIR, acceptance criteria for each information requirements and LoIN. To facilitate understanding the rules about these various aspects to be considered by the LAP will be examined in the ensuing paragraphs.

8.4.1. a1. Check compliance with MIDP deliverables

InformationModel(?model)^ MasterInformationDeliveryPlanMIDP (?deliverable)^compliesWith(?model, ?deliverable)- > ApprovedDeliverable(?model) (r-8)

8.4.2. a2. Ensure alignment with appointing Party's EIRs

InformationModel(?model)^AppointingPartyEIR(?eir)^alignsWith(?model, ?eir)- > EIRCompliant(?model) (r-9)

8.4.3. a3. Ensure alignment with lead appointed Party's EIRs

InformationModel(?model)^LeadAppointedPartyEIR(?eir)^alignsWith(?model, ?eir)- > EIRCompliant(?model) (r-10)

8.4.4. a4. Verification of acceptance criteria

8.4.4.1. Verification of appointing Party's acceptance criteria. InformationModel(?model)^hasLevelOfInformationNeed(?model, ?level) ^meetsCriteria(?level, ?criteria)- > LevelOfInformationApproved(?model) (r-11)

8.4.4.2. Verification of lead appointed Party's acceptance criteria. This is about verifying whether MIDP, EIR for the AP and EIR for the LAP comply with the acceptance criteria.

For the EIR for the AP, many acceptance criteria exist and can be checked for compliance with the AP. Two examples of criteria for EIR for the AP that can be checked are.

- The information in the EIR must comply with relevant industry standards, legal requirements, and best practices. This includes adherence to data formats, protocols, and modelling standards.
- The EIR must contain a section for hardware and software with indicating all file types and interoperability formats.

MasterInformationDeliveryPlanMIDP(?p) ^alignsWith(?x, ?p)- > AuthorisedInformationContainer(?x) (r-12)
AuthorisedInformationContainer_AP(?x) - > sqwrl:select(?x) (r-13)
MasterInformationDeliveryPlanMIDP(?x) ^alignsWith(?x, ?p)- > AuthorisedInformationContainer_LAP(?x) (r-14)
AuthorisedInformationContainer_LAP(?x) - > sqwrl:select(?x) (r-15)
InformationModel(?model)^hasFileType(?model, ?format)^meetsCriteria(?level, ?format)- > AuthorisedInformationContainer(?model) (r-16)
AuthorisedInformationContainer(?IM) ^ hasFileType(?IM, ?format) ^ - > sqwrl:select(?IM) (r-17)

8.4.5. a5. Verify level of information need

InformationModel(?model)^hasLevelOfInformationNeed(?model, ?level)^meetsCriteria(?level, ?criteria)- > LevelOfInformationApproved(?model) (r-18)

Use case 4-b Review and accept the information model (by the AP)

8.4.5.1. Submit information model for authorisation. r-12, r-13, r-16 and r-17.

TaskTeam(?TT) ^ LeadAppointedParty(?LAP) ^ submitsTo(?TT, ?LAP) ^ InformationModel(?IM) ^ reviews(?LAP, ?IM) - > ReviewAndAcceptInformationModel(?IM) (r-19)

8.4.6. Explanation of the rule "01-rule-4"

- TaskTeam (?TT):Identifies a team responsible for a task (presumably related to BIM)
- LeadAppointedParty(?LAP): Identifies the lead party appointed for the project

- submitsTo(?TT, ?LAP): Indicates that the Task Team submits something (like reports, models, documents) to the Lead Appointed Party.
- InformationModel(?IM): Specifies that the subject of the submission is an Information Model.
- reviews(?LAP, ?IM): Suggests that the Lead Appointed Party reviews the Information Model.
- ReviewAndAcceptInformationModel(?IM): This part of the rule triggers when the preceding conditions are met, indicating that the Information Model is reviewed and accepted

8.4.7. Explanation of the query “02-query-4”

ReviewAndAcceptInformationModel (?IM) - > sqwrl:select(?IM)

This query is used to select and list all Information Models that have been reviewed and accepted based on the criteria set in the rule. It’s a way to extract specific instances where the rule has been applied successfully.

All the rules in the preceding paragraphs were implemented and tested in SQWRLTab in Fig. 12.

For illustrative purposes, only r-0-Test and r-1-Test will be explained. The r-0-Test query is designed to interrogate BIM-OIM and identify all information containers (Step 1 in Fig. 12). Once these information containers have been retrieved, the r-1-Test query is then executed to list their respective names (Step 2 in Fig. 12). As shown in Fig. 12, the Crossrail instances precisely match the original data as extracted from the Crossrail Ltd (2017) document.

The process was iterative, involving repeated cycles of running the program, identifying errors, and making corrections until a result with reasonable responses was achieved.

9. BIM-OIM evaluation

Ontology evaluation is the broadest concept that assesses the quality of an ontology based on specific criteria such as accuracy, completeness, usability, and consistency. It determines how well an ontology meets its intended purpose and its fitness for use.

Ontology evaluation typically includes both verification and validation. Verification ensures that the ontology conforms to its specifications and requirements, focusing on internal correctness rather than real-world applicability. Ontology verification ensures that the ontology is constructed correctly according to its formal specifications, without structural or logical errors. On the other hand, validation assesses whether the ontology accurately represents the intended domain or knowledge, often employing qualitative and quantitative methods. It ensures that the ontology correctly represents the intended domain and meets user expectations. It focuses on whether the ontology is useful and meaningful in real-world applications. Both verification and validation are crucial components of ontology evaluation, ensuring the ontology’s correctness and relevance to the modelled domain.

In the case of BIM-OIM, the verification was iterative and conducted throughout the development process. It involves checking the ontology’s consistency, completeness, and correctness using reasoners. The HermiT (version 1.4.3.456) reasoner, a plugin Protégé-

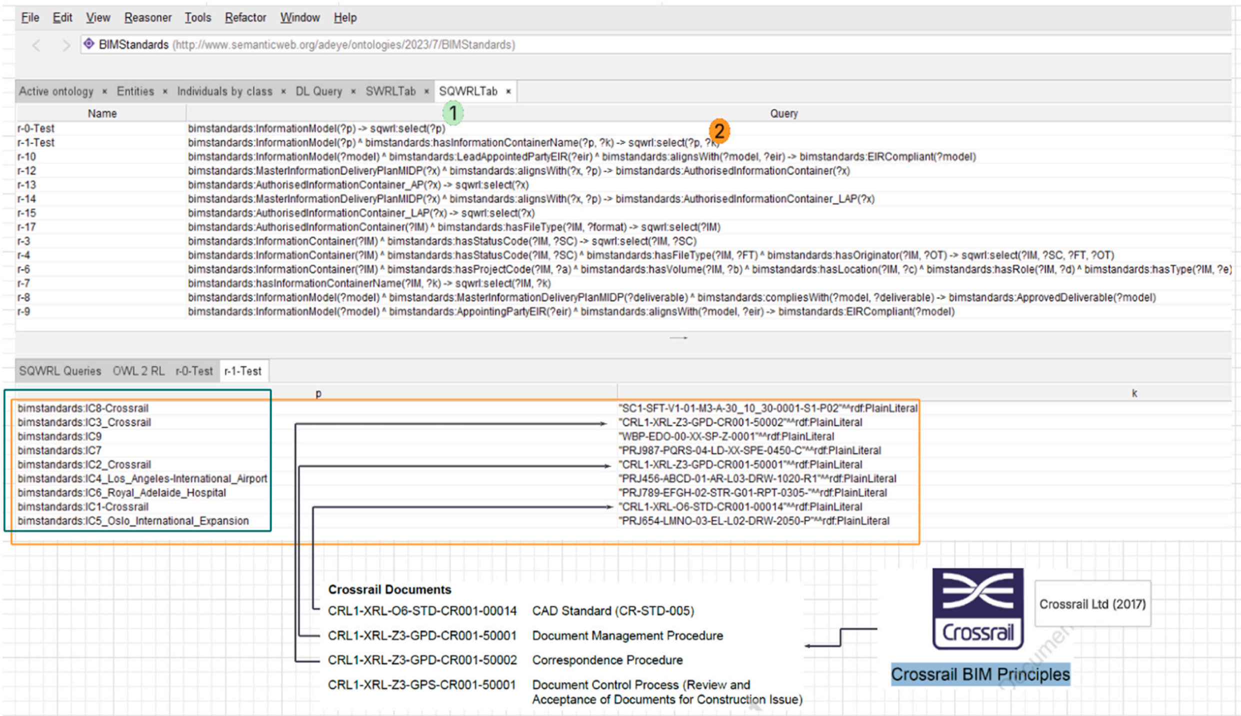

Fig. 12. BIM-OIM rules.

OWL was used. When the reasoner was run, errors were generated which were corrected and re-run iteratively until no error messages were generated. For illustrative purposes, an example of how an error was/is dealt using Hermit will be examined. To facilitate understanding the screenshot of the process is presented in Fig. 13.

After an iterative process of verification, the BIM-OIM was confirmed to be functional and error-free. In Step A, datatype properties were validated without errors, particularly the property hasFileFormat, which correctly had a Range of string and an output of.RVT. In Step B, an error was intentionally introduced by changing the Range to an integer. Running Hermit in Step C detected an inconsistency, prompting further investigation in Step D to determine the cause. This inconsistency was visually reflected in Step E, where the class hierarchy of the datatype properties appeared in red, indicating a structural issue compared to Step A. The authors then manually corrected the error and re-ran Hermit, producing a consistent output in Step F. While Protégé's built-in reasoners (Hermit and ELK) were efficient in verifying the BIM-OIM, they were not suitable for verifying SWRL rules, as they do not support SWRL built-in atoms. However, this was not a limitation, as SWRLTab and SQWRLTab are inherently designed to self-validate rules edited by developers. These tools do not execute any rules containing errors. Consequently, the authors refined the SWRL rules as per their design and ensured that any errors were resolved before execution. This approach guaranteed that all rules incorporated into SWRLTab and SQWRLTab were fully functional and error-free.

The validation was conducted in 2 stages. Firstly, to ensure the ontology is valid, the concepts were elicited from standards such as ISO 19650, thesis [69], UK BIM Framework and existing ontologies such as the digital construction ontologies (Törmä and Zheng, 2020). This approach is consistent with Ren et al.'s (2021). However, this is considered semi-validation as these concepts have been drawn from different sources and may not necessarily fit when brought together. This led to a second validation, where experts were involved. A total of 6 experts with experiences in BIM standards and construction informatics background participated in the interviews and provided feedback that was used in refining BIM-OIM (See Table 2). This is necessary because the initial findings can be biased to the authors' knowledge and, therefore, should be modified by experts [79].

A demo about the different concepts of ontology was presented to the different participants separately. They were asked questions about the different aspects of BIM-OIM. Firstly, they were asked if BIM-OIM ontology was an accurate representation of the domain of ISO 19650. All the participants confirmed that the BIM-OIM ontology was a perfect representation of the parts that it was intended for. Secondly, the participants were presented with the rules in SQWRL and asked if the rules reflected typical challenges faced in using ISO19650 standards. The findings from this interview and the entire study will be discussed in section 10.

10. Findings and Discussions

The main goal of this study was to develop a BIM-OIM that makes BIM process data available and more easily useable. In other words, the developed BIM-OIM can allow other researchers and practitioners to better find, implement, cite and reuse it in their various

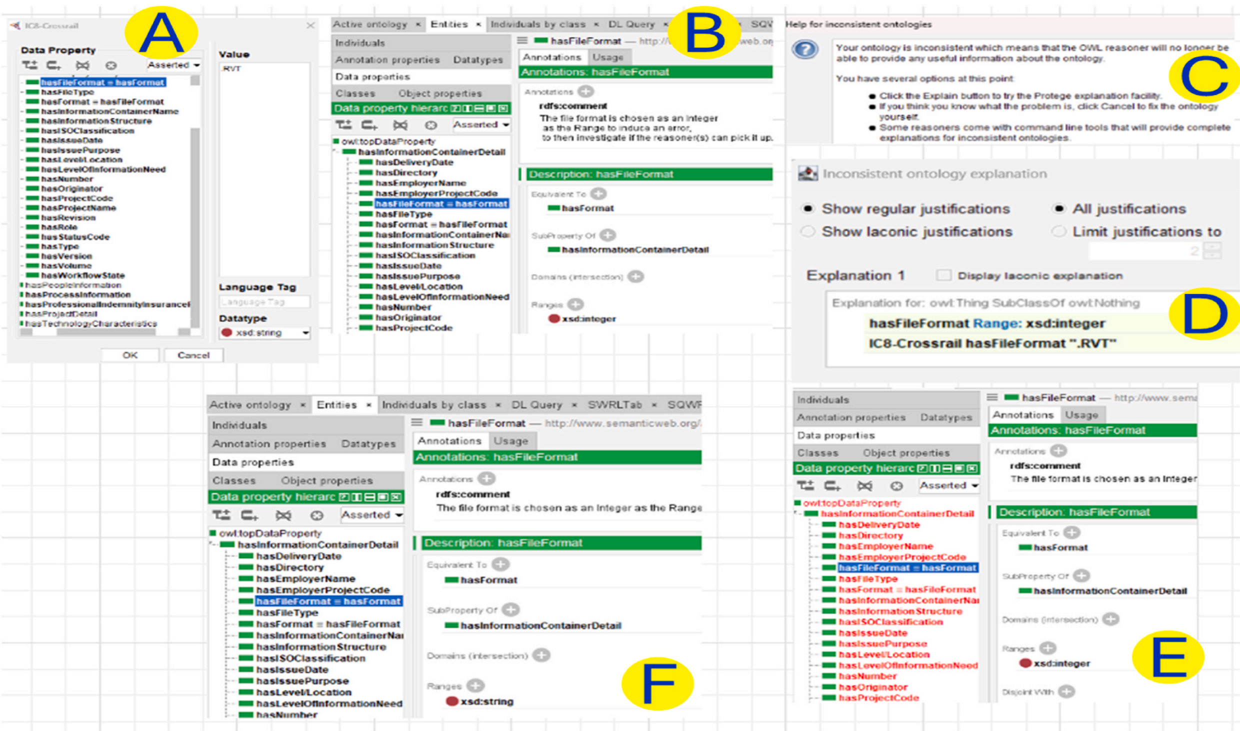

Fig. 13. Consistency checking/Identification of errors using Hermit.

Table 2
Level of experiences of interviewees in BIM, ISO 19650 and Semantic web/Ontology.

		Expert	Advanced	Intermediate	Beginner	Novice
Interviewee A	BIM	x				
	ISO 19650	x				
	Semantic Web/Ontology			x		
Interviewee B	BIM		x			
	ISO 19650			x		
	Semantic Web/Ontology		x			
Interviewee C	BIM			x		
	ISO 19650				x	
	Semantic Web/Ontology		x			
Interviewee D	BIM		x			
	ISO 19650		x			
	Semantic Web/Ontology			x		
Interviewee E	BIM		x			
	ISO 19650		x			
	Semantic Web/Ontology	x				
Interviewee F	BIM				x	
	ISO 19650				x	
	Semantic Web/Ontology	x				

practices. The BIM-OIM overcomes the inherent difficulties in comprehending and operationalising ISO 19650 standards, thereby facilitating their adoption during the delivery of construction projects.

To achieve the aim of the study, a combined approach using two information-sharing paradigms, BIM and ontology engineering, was used. The integration of both methods enhances the possibility of finding project information and seamless collaboration in the delivery of construction projects, thereby widening the adoption and implementation of BIM standards on construction projects. This has the potential to alleviate the fears and barriers that have been hindering BIM uptake in construction projects. The integrated method led to the achievement of the set research outcomes.

Firstly, the key concepts in BIM standards and specifications, as well as their relationships, dependencies, and constraints between the key concepts, were abstracted and modelled using ontological machine-processable format. The ISO 19650-1&2-2018 served as the basis for the developed BIM-OIM. This is because ISO 19650-1&2 are the two leading global standards recommended for use on BIM stage 2 projects. In developing the BIM-OIM ontology, the main concepts, most of which are ISO 19650 clauses, were used. Main classes were identified and used in the BIM-OIM ontology. For example, concepts were extracted from clauses 5.4 and 5.7 of ISO 19650-2., i.e., “Appointment” and “Information Model Delivery” respectively. Other concepts that were captured include constraints and equivalent relationships. An example of a constraint is the definition of the uniqueness of information containers. For equivalent relationships, a practical case is that of a BIM Stage 2 project. A project that has been delivered at BIM Stage 2 is a BIM-compliant project and vice-versa. For relationships, object properties between the concepts in the BIM-OIM were modelled. For example, the relationship between the Appointing Party and the Lead Appointed Party. This “isAppointedBy” and inverse as “Appoints” object properties were established.

To ensure the BIM-OIM is robust, useful, and fit for its intended purpose, provoking questions were used to further assess this. The questions were whether: it was/is easy to understand BIM-OIM? aligned with the ISO 19650 standards, BIM-OIM was comprehensive?

With respect to clarity and understanding, the feedback from the six interviewees on the clarity and ease of understanding of the BIM-OIM in relation to ISO 19650-2 concepts is overall very positive, with each expressing a high level of comprehensibility. Here are some notable highlights of their responses.

Interviewee D found the ontology quite easy to understand, particularly praising the use of simple English in defining properties such as "isAcceptedBy, isApprovedBy, isDeliveredBy." Interviewee B affirmed the clarity of the BIM-OIM, crediting the annotations for enhancing understanding. Interviewee E praised the Equivalence Classes and how they capture the relationship between BIM Stage 2 and BIM-compliant projects, enhancing clarity. Interviewee C described the BIM-OIM as clear despite its detailed content, noting that even novices should be able to navigate the ontology effectively, with annotations adding significant value.

These insights collectively suggest that the BIM-OIM’s design and structure, including its annotations and straightforward language, make it accessible and easy to understand for those familiar with ISO standards and even for those new to the field. This user-friendly approach seems to significantly facilitate the learning and application of BIM-OIM principles aligned with ISO 19650-2 standards.

With respect to BIM-OIM alignment with ISO 19650-1&2, all the interviewees’ responses suggest a consensus that BIM-OIM aligns well with the ISO 19650-2 standard. Some notable points from interviews include.

- The fact that BIM-OIM adopts the language used in ISO 19650-2 makes it easier to establish the alignment between both (Interviewee F).
- Interviewee A stressed that BIM-OIM not only aligns with ISO 19650-2 but also "brings it to life" suggesting that BIM-OIM serves as a dynamic, living connection that enhances the usability and application of the ISO standard. In fact, in the words of interviewee A, “BIM-OIM is the brain of ISO 19650-2 hard copy manuscript, as it is dynamic and can be used in reasoning over it for informed decision-making”.

- Interviewee D: While affirming that BIM-OIM covers the necessary ISO 19650-2 scopes, also noted that it extends beyond by including properties like data types and annotations. The interviewee noted that annotations enhanced understandability. They suggested that it could be improved by detailing the outputs like documents or deliverables expected from different stakeholders, such as task teams and appointed parties.

Although these responses collectively indicate a strong validation of BIM-OIM's alignment with ISO 19650-2 standards, the suggestion for further detailing deliverables from actors in the, e.g., task teams, highlight an area for potential enhancement to ensure the ontology is complete and improve its practical application. These authors took this on board and revised the ontology by including all the deliverables from the actors stated in ISO 19650-2 and BIM-OIM.

Lastly, concerning comprehensiveness, the interviewees acknowledged the BIM-OIM's comprehensive coverage of essential BIM aspects and its alignment with ISO 19650-2.

Secondly, a key objective was to implement rules within the BIM-OIM ontology framework. To this end, SWRL was used to modelled rules in BIM-OIM. These rules are intended to facilitate automated reasoning and decision-making processes, enhancing the effectiveness of information management in BIM. The rules leverage the structured knowledge representation provided by the integrated ontology and the logical inference capabilities of SWRL rules. A number of use cases about BIM applications in information management using ISO 19650 were discussed. The first use case focused on rules that allowed straightforward interrogation and retrieval of facts or data from BIM-OIM. Data retrieval is a major task carried out on data models. This is achieved using Semantic Web data modelling, which allows reasoning, made possible through a combination of rule and query languages. The query component is achieved using SQWRL, while the rule part is achieved through SWRL. An example is the retrieval of the various BIM Stage 2 compliant projects. Another example is the retrieval of certain types or information containers and their respective authors or originators. Lastly, some concepts in ISO 19650 required forward chaining rules. For example, a rule that establishes that a reviewed information container has been accepted (antecedent), is sent to the "consequent" ReviewAndAcceptInformationModel concept. A separate query is developed with ReviewAndAcceptInformationModel as the new "antecedent" and the accepted information containers are retrieved as a "consequent" using the sqwrl:Select function (See "01-Rule-4)

Given that the SWRL rules are based on ISO 19650, it is essential to verify whether these rules are consistent with the knowledge and guidelines outlined in the ISO 19650 standards. Out of the six interviewees, five confirmed that the SWRL rules embedded in BIM-OIM aligned or reflected common applications in practice. Interviewee F did not provide any views because, although an ontology expert, they had limited practical knowledge of BIM. The main highlights of the interview are examined in the ensuing paragraph. Interviewee D appreciates the clarity the rules provide, noting they "make it easier for them to know what should be done" and can enhance compliance and reduce errors. This contrast with the hardcopy manuscript of ISO 19650 which is "susceptible to various interpretations by humans. Interview B corroborates the views of D by stating that the SWRL rules are helpful for "check[ing] approvals, acceptance, and reviews," suggesting a direct usefulness in regulatory and procedural contexts. This corroborates Interviewee C who express a very positive view about the rules' power and intelligence, particularly in naming conventions which assist greatly with interoperability and information sharing. Interviewee E focuses on the representational aspect, suggesting that the rules can be embedded to handle quantitative data, timelines, and penalties, thus covering a wide range of practical needs in project management. These aspects were considered and the BIM-OIM revised to consider these aspects.

Thirdly, it was imperative to evaluate the BIM-OIM to make sure it is of high quality, performance and effectiveness and whether it truly reflects the intended ISO 19650 knowledge. This was achieved using reasoners and experts. The Ontology reasoners were used to check for technical consistency in the ontology. This was an iterative process conducted throughout during the ontology development. For the semantic correctness, concepts were abstracted from ISO19650, PhD thesis by Akintola [69] and existing ontologies. These concepts were used in developing the BIM-OIM ontology. Experts were used to validate the developed concepts through interviews to avoid bias from the authors' interpretation and representation of facts. Upon completing the evaluation, it was crucial to determine how the ontology could be utilised in the future and identify potential areas for further development. To address this, interviewees were asked about the future practical applications of the ontology and possible advancements that could be undertaken.

There was a consensus by all six interviewees that given BIM-OIM is an ontology, it can be used or extended for use in different construction domain applications. Some specific highlights include Interview E who stated the BIM-OIM can be used to capture information about cost control and project management, with specific focus on dealing with cost and time overruns. Interviewee D stated that BIM-OIM can be used for "check[ing] approvals, acceptance, and reviews and compliance checking in general. The six interviewees stated that a user-friendly web-based interface (Semantic Web -based platform should be developed to sit on top of BIM-OIM. Interviewees A and E recommended considering "many examples of applications or use case," believing this will attract more interest.

Upon completing the evaluation of BIM-OIM, it is imperative, as with any ontology, to establish its generalizability and scalability across varying project complexities. While the Crossrail case study offers valuable insights into the ontology's performance in the context of a mega project, it is equally essential to assess how BIM-OIM performs across a spectrum of project types, including both larger and smaller-scale developments. This includes scenarios such as residential buildings or infrastructure projects that involve fewer stakeholders and reduced data complexity. Understanding the ontology's adaptability to such varied contexts is crucial to substantiate claims of its broader applicability.

To this end, two key performance parameters were considered in evaluating BIM-OIM: the accuracy of error detection and the speed of execution. In terms of error detection accuracy, intentional errors were introduced within the ontology dataset, as illustrated in Fig. 13 of the manuscript. The HermiT reasoner consistently and successfully identified these errors across multiple trials. This outcome demonstrates the robustness of BIM-OIM's logical structure, indicating that the ontology can reliably detect inconsistencies regardless of variations in data volume or project complexity.

With regard to execution speed, the operational efficiency of BIM-OIM was assessed by observing the time required to load the ontology in Protégé and the speed at which rules and queries are executed. Several critical factors influence this performance.

These include the overall size of the project, the diversity of stakeholders involved, the volume of data processed, and specific design choices made during the ontology's development. Such design choices encompass the depth and breadth of the class hierarchy, the density of logical axioms, the number of property restrictions applied, and the incorporation of complex constructs such as disjoint unions and cardinalities. Additionally, the choice of reasoner is a vital consideration, with HermiT being employed in this case.

While Protégé has demonstrated the capability to handle ontologies at a significant scale, performance bottlenecks tend to emerge during reasoning-intensive tasks, such as checking consistency, inferring class memberships, and executing SPARQL queries or SWRL rules. To provide a meaningful benchmark for BIM-OIM's performance, a comparative analysis was conducted against ifcOWL, a well-established large-scale ontology developed by Beetz et al. [80]. This comparison revealed that BIM-OIM is considerably leaner across most ontology metrics, a characteristic that contributes positively to its performance efficiency (See Table 3). Specifically, BIM-OIM contains fewer axioms, classes, and properties than ifcOWL, making it more agile and responsive during operational tasks, while still maintaining robust reasoning capabilities.

Both ontologies load in Protégé in under a minute. BIM-OIM, having a leaner structure, benefits from shorter load times and faster reasoning tasks, especially when compared to ifcOWL. Moreover, potential challenges such as consistency checks, class inferences, and SWRL rule executions have been validated successfully within BIM-OIM, as demonstrated in Sections 7, 8, and 9 of the manuscript. These validations confirm that BIM-OIM maintains its functional integrity across diverse project scales and complexities.

In summary, although BIM-OIM has demonstrated its efficiency and robustness within the Crossrail case study, its underlying design principles, supported by performance benchmarking and rigorous error detection evaluations, suggest that it is equally well-suited to projects of varying complexities. Whether applied to smaller residential developments or more intricate infrastructure projects, BIM-OIM's adaptable structure allows it to accommodate diverse data environments and stakeholder needs. Notably, in the ontology, Crossrail is modelled as an instance serving primarily as a placeholder. Consequently, in the context of BIM-OIM and with other ontology concepts constant, the notion of varying project complexity is largely reflected in the range and diversity of properties within the ontology, these can expand or contract depending on the specific demands of the project size and scope. Nonetheless, it is essential to emphasize that maintaining scalability and performance across different project types relies on strict adherence to established best practices in ontology development. Careful management of class hierarchies, property definitions, and logical constructs remains fundamental to ensuring BIM-OIM's continued effectiveness in real-world applications.

11. Conclusion

The study developed a BIM-OIM that makes BIM process data available, more and easily useable, in other words, which can allow other researchers and practitioners to better find, implement, cite and reuse it in their practice. Due to the practice-driven-goal of BIM-OIM, the pragmatism paradigm coupled with YAMO, one of the leading ontology engineering methodologies, was used. BIM and Ontologies share commonalities in terms of structuring information and utilising ontological representation, thus integrating both and harnessing their benefits for improved information management and interoperability. The BIM-OIM output is a transformed information-rich ontology that is represented as concepts, properties and relationships, including constraints, which facilitate understanding. The clarity and comprehensibility of BIM-OIM, as affirmed by 6 out of 8 interviewees, suggest its potential to drive adoption and facilitate efficient implementation throughout the information management lifecycle of projects. The core knowledge domains in this model have been meticulously and explicitly represented, and their adaptability is extendable to applications beyond BIM implementation in practice. BIM-OIM is versatile and can be employed for purposes beyond BIM EPs, offering both a static structural view of knowledge and a dynamic one that can be easily queried and customised to various needs. Additionally, the BIM-OIM can potentially facilitate BIM standards compliance tracking and checking to ensure regulatory requirements are met using an audit of information that can also assist in the enhancement of collaboration, trust and the prevention of disputes.

Developing comprehensive and accurate ontologies such as BIM-OIM can be a complex and time-consuming process, requiring deep domain expertise and often extensive manual effort. While the BIM-OIM ontology development tools can facilitate interoperability and reuse amongst different stakeholders, they are still technically dependent on specialised or knowledge engineering software. The implication of this is that only experts can exploit BIM-OIM. As part of future studies, exploring the expansion and development of other BIM-OIM relevant concepts using generative AI will be imperative.

Also, it will be imperative to develop a semantic web-based system of BIM-OIM. Such a system should be user-friendly and easy for experts as well as non-experts to use. For example, the system should allow practitioners to use the ontology through drag-and-drop tools, forms, or templates. Another aspect to consider is to ensure that BIM software as well as ontology engineering software can process BIM-OIM. Part of our future study will focus on developing plugins that will export BIM-OIM into conventional BIM software, thereby fostering interoperability between BIM and ontology engineering software systems. This will potentially improve the adoption of BIM in practice, as importing ontological ISO 19650 into any BIM platform will ease its integration into projects and hence ease of use. Finally, while the case study focuses on the Crossrail project, its use cases are designed to be applicable to a wide range of projects. However, to ensure scalability, the ontology's modular and extensible structure should be leveraged to incorporate the specific requirements of various project types, such as residential, commercial, and infrastructure developments.

Table 3
Ontology Metrics: BIM-OIM vs ifcOWL.

	BIM-OIM	ifcOWL
Axiom	1030	17 817
Logical axiom count	568	11 790
Declaration axioms count	344	3555
Class count	186	1101
Object property count	74	1422
Data property	68	5
Individual count	17	1018
Annotation Property count	3	15

CRediT authorship contribution statement

Abanda F.H: Investigation, Conceptualization. **Akintola A:** Writing – original draft, Methodology. **Tuhaise V.V:** Writing – original draft. **Tah J.H.M:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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