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# Knowledge-based OpenBIM data exchange for building design

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ABSTRACT

Building design is highly complex as it involves numerous professionals and their interactions, hence with diverse tools used and multi-resources and different structured data and information required to be processed. Despite the existing efforts to develop multi-objective decision making tools to support complex design, most of the research face difficulties to provide holistic, dynamic and collaborative knowledge base due to the complexity of the information interoperability issues across different parties and throughout life cycle. This paper developed an automatic data exchange framework that combines only the necessary data from BIM models using semantic web technology to eliminate inefficiencies in data exchange and improve decision-making early in the design stage. The proposed data acquisition method can produce a dynamic knowledge base to connect both static and dynamic information. A multi-objective knowledge base was developed to assist engineers associated with sustainability and cost in comparing different design options based on the existing BIM data. The proposed ontology was developed using a machine-readable format, allowing the ability to add more concepts to it in the future and work with other automated tools. The validated framework could reduce human involvement and errors while providing more efficient ways to leverage diverse information sources together to support holistic decision-making for building design.

## 1. Introduction

The construction industry is changing its traditional business methods, with information being exchanged digitally rather than in paper form. However, moving forward with this digitalization requires adopting new techniques to collaborate more effectively in the design stages. Building information modelling (BIM) has been utilized to facilitate project collaboration and integration [1]. However, data exchange within BIM is still facing challenges in reaching a high level of advancement. Lee [2] mentioned four main issues behind data exchange: (1) incomplete coverage of a data model; (2) issues with translators due to the lack of guidelines while developing these tools; (3) system errors from using many vendors' tools; and (4) software domain complications. Consequently, this data fragmentation causes a research gap in cross-disciplinary decision-making.

The decision-making has mainly focused on individual aspects such as economic concerns, environmental impact, and safety. These aspects are developed separately and based on available information and engineering knowledge. However, for complex building design, many factors need to be considered to achieve design optimization; therefore, it is challenging to enable efficient collaboration. Providing a linked design can improve cooperation between disciplines and design teams. Consequently, linking data sources from diverse aspects can obtain a feasible solution early in the design stage by examining several factors holistically, mainly because it is possible to have more than one design solution. Structural engineers, for instance, can reduce carbon content and cost by assessing alternative construction materials while considering design criteria. A study by Pauwels et al. [3] showed that the semantic web could contribute to applications involving information from various disciplines. The semantic web has several features [4]. It provides a framework and language for designers to organize and represent information in a format both humans and machines can understand. It establishes a hierarchical structure of the concepts in a particular domain and describes their connections. Consequently, it can be used to align concepts from AEC disciplines. The semantic web has been applied to cost estimation [5–8]; energy management [9]; building evacuation design [10]; BIM design process [11], and safety in facility management [12]. It has also been used to support environmental monitoring and compliance checking among different information systems [13]. Consequently, it can improve interoperability by implementing domain

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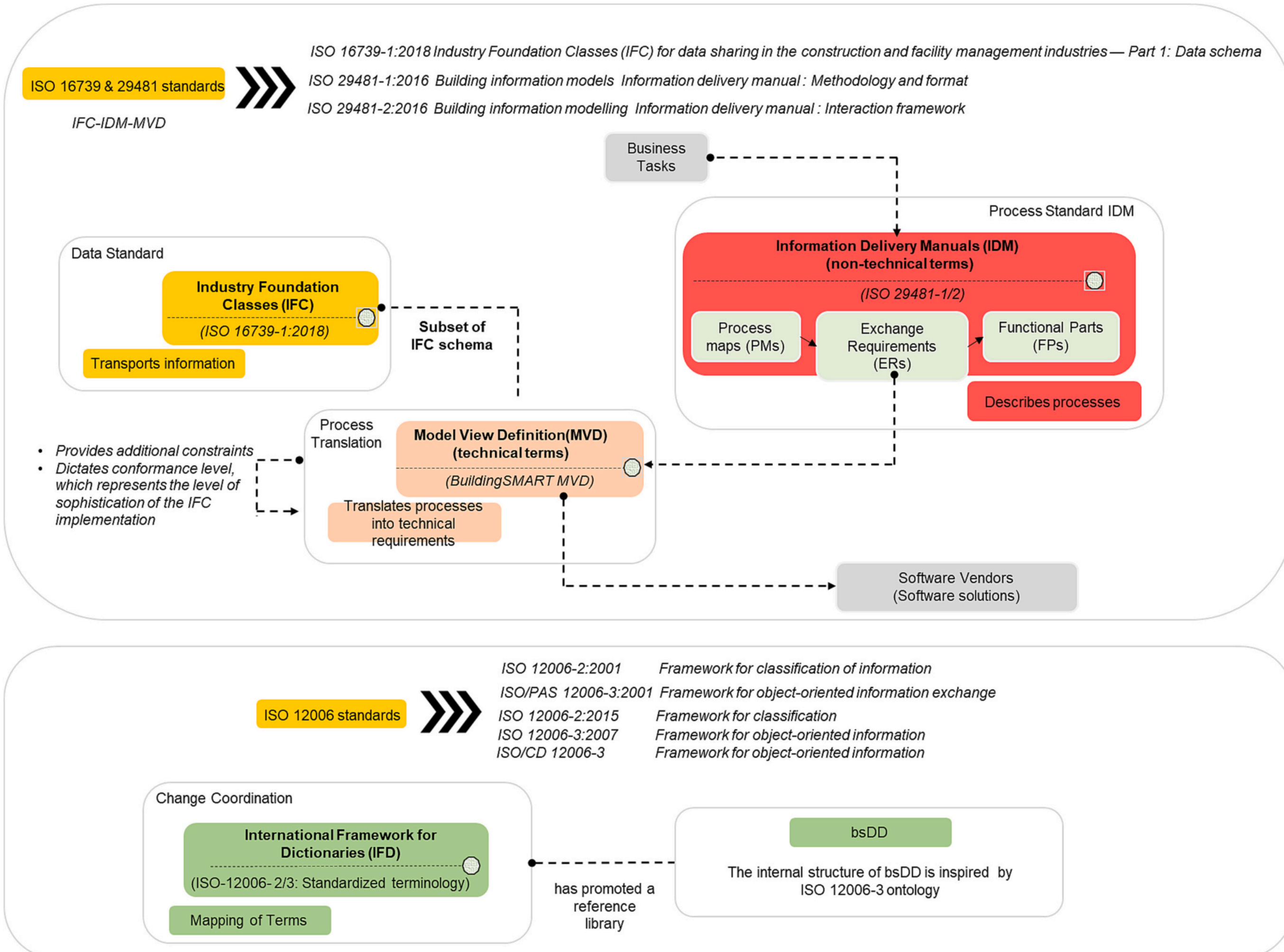



**Fig. 1.** The relationship between IFC, IDM, MVD and other concepts.

knowledge into the BIM model. However, most research was developed separately to serve a single objective decision. There is no method to automatically associate the data from a BIM model with multi-objective knowledge base approaches to produce a holistic decision. Most research requires manual input to process the data in a BIM model.

This paper aims to establish an automatic data-exchange framework that combines a data-exchange method and semantic web technology to eliminate inefficiencies in data exchange and improve decision-making early in the design stage. The scenario-based case testing showed that the framework could (1) process the IFC-based BIM model correctly; (2) automate the manual calculations; and (3) generate new facts based on the IFC file data using the defined SWRL rules, which allowed the end-user to compare different design alternatives.

This paper has seven sections. After the Introduction in Section 1, the Literature review is presented in Section 2. The Research methodology is explained in Section 3. Section 4 presents a data exchange method that extracts critical data from a BIM model. It was implemented based on the concepts and datasets defined in previous work by Khudhair et al. [14], which forms the basis for the proposed framework from a data processing perspective. In Section 5, a multi-objective knowledge base was implemented, which assists engineers who lack knowledge associated with sustainability and cost to compare design choices while considering conditions to develop an ideal design. The main contribution of this paper lies in providing a multi-objective knowledge base that closely connects to project data. Consequently, an automatic data acquisition method was developed to align the proposed knowledge base. The proposed method automatically extracts data and merges it with the data presented in the developed ontology, eliminating human involvement by decreasing manual input. Section 6 addresses the testing and validation of the proposed framework. A scenario-based case study is carried out to demonstrate the developed framework. Finally, the Conclusion is given in Section 7.

## 2. Literature review

### 2.1. Interoperability within BIM

The massive increase in information compiled from various design tools has posed challenges in data exchange and complicated the decisions made within a project. Interoperability, which is described as the ability to exchange data seamlessly across disciplines and stakeholders [15], is an issue that cannot be solved immediately. It is a lifetime process that should be maintained and updated as new technologies and concepts become available in the industry [16]. Turk [16] mentioned three levels of interoperability that need to be considered. Firstly, the technical level provides communication between systems by adopting various technologies and tools. Secondly, the semantic level focuses on a shared, common vocabulary exchanged among the participants in a project that retains its meaning when various tools are involved. The major issue in semantic interoperability is the openness of systems. Moreover, he identified various classifications of interoperability realization: (1) the federated model, which is based on a single common

**Table 1**
Various versions of the IFC schema.

| Version | Release year | Main enhancement |
|---|---|---|
| IFC2 | 2000 | Introducing the concept of a core model and domain extensions |
| IFC 2 Add1 | 2001 | Fixing issues related to IFC2 |
| IFC 2 × 2 | 2003 | Included several extensions related to the architecture, building control, construction management, facility management, HVAC, and structural domains |
| IFC 2 × 2 Add1 | 2004 | Fixing issues related to IFC 2 × 2 |
| IFC 2 × 3 | 2006 | Improving the quality of the old versions of IFC 2 × 2 |
| IFC 2 × 3 TC1 | 2007 | Fixing issues related to IFC 2 × 3 |
| IFC 4 | 2013 | Enhancing the schema capability in its main architectural, building service and structural elements and enabling the extension to infrastructure. Moreover, enabling new BIM workflows, product libraries, and BIM-to-GIS interoperability. |
| IFC 4 Add1 | 2015 | Fixing issues related to IFC 4 |
| IFC 4.3 | Underdevelopment | focusing on infrastructures such as ports and harbours. |

reference model; (2) the unified model, which is based on using open standards to exchange information, such as IFC; and (3) the master model, which uses proprietary information model database. Thirdly, the organizational level focuses on data access and uses procedures and guidelines. Similarly, OnSteel, Drogemuller and Toth [17] classify interoperability into four levels. The first level is limited to providing a successful file exchange among tools, while the second level extends this by parsing the exchanged file correctly. The third level concentrates on the visualization aspects of the exchanged model among different tools. The fourth level is the most critical, where models must be semantically rich. This level requires understanding the intention behind the exchange of models and considering data consistency to avoid data loss. Consequently, it is shown that enhancing interoperability is concentrated on solving issues related to the openness of systems and business integration.

### 2.2. Defining and standardizing information delivery

The OpenBIM concept, which was developed as an expansion for BIM, consists of several concepts and components (Fig. 1) that have been developed by buildingSMART International (bSI). Some of these concepts are IFC; information exchange methodology (IDM), which is used to “capture and specify processes and information flow during the lifecycle of a facility” [18]; the International Framework for Dictionaries (IFD), a flexible method linking existing databases with construction information; and buildingSMART Data Dictionary (bSDD), a library of object concepts and their properties based on IFD standards for all types of entities, properties, and classifications that help users find the right classifications, properties, and values.

Various versions of IFC were released (Table 1). However, there was a six-year period between the IFC2x3 TC1 and IFC4, indicating a major development in the schema. The latest versions show a vast expansion of the IFC schema. For instance, in the beginning, the schema was built to cover the building domain. The latest versions have been expanded to include the infrastructure domain. This expansion makes the schema complex and requires more effort to understand, especially by non-experts.

Because the IFC schema covers various domains, it is not convenient to implement the entire schema in software vendors. To solve the concerns within the IFC schema, buildingSMART proposed the IDM and Model View Definition (MVD) concepts [19]. IDM is composed of a project map (PM), exchange requirements (ERs), and functional parts (FPs) [20]. The PM helps define the overall workflow and detailed tasks in one or more disciplines. This map defines what information needs to be created and exchanged. The FPs link this information to a schema by matching it to the correct entity to support software solutions, which form the initial steps to develop MVD. The development process of an IDM-MVD is complicated and time-consuming [15], which causes several challenges that constrain their adoption [21].

The flexible nature of the IFC schema leaves room to map the same information in diverse ways [15]. This mainly depends on the developers, especially because there is no clear, logical connection between the units of information in the exchange requirements of an IDM or an MVD [22]. IFC was not designed to determine new information from a BIM model but to deliver information to end users without any reasoning functionalities. Although cost estimating applications are moving towards IFC compatibility, IFC does not solely cover all components required to generate an estimate, as estimating requires not only quantity take-off data but other types of associated databases [23]. IFC needs to be supported by other technologies or formats to enhance its performance, necessitating the use of technologies from computational areas to work with BIM models. Consequently, technology such as the semantic web can enrich the IFC model by deducing new facts.

### 2.3. Enhancing interoperability through a unified data exchange method

Several research articles have focused on enhancing data exchange. Qin, Deng and Liu [24] built a framework to manage the information between architectural and structural disciplines. They identified that the lack of a unified method limits data exchange among diverse disciplines and results in integration issues [24]. Wang, Yang and Zhang [25] developed an IFC-based software tool for structural model conversion, which helped extract the required information to form the required structural model. Hu et al. [26] proposed a unified data model and developed a web-based platform based on IFC and algorithms to solve interoperability issues between architectural and structural models. They stated that there is a lack of techniques based on using a common data model where all the data is standardized. Similarly, Ramaji and Memari [27] developed an approach to transform the architectural model into a structural analytical model using the architectural coordination view as a starting point for this conversion.

Few studies have explored providing information to other downstream processes. Won et al. [28] proposed an algorithm to extract a partial IFC model without using the data structure, where they used a pre-specified set of building elements as input. They stated that an extraction algorithm is semantically successful if it can preserve the same semantic relationships before extraction without any data loss. Zhang et al. [29] used web ontology language (OWL) to extract a partial BIM model. They mentioned that processing the IFC against the ontology is the most crucial step in the development. Moreover, Gui et al. [30] developed a method to extract domain-specific information to remove unrelated IFC data. They stated that although several collaboration platforms have been developed with a central BIM database, the model becomes hard to manage as the model size increases and results in inefficient data sharing.

### 2.4. Semantic web and the underlying resources for knowledge base development

A survey conducted by Bhatija, Thomas and Dawood [31] showed that many AEC industry stakeholders remain unaware of knowledge management ideas. However, the majority agreed on the importance of

**Table 2**
Fire resistance time based on Eurocode 2 [32].

| Fire resistance per minute | Minimum column width (mm) | Minimum concrete cover (mm) |
|---|---|---|
| R60 | 200 | 25 |
| R90 | 300 | 25 |
| R120 | 350 | 25 |

sharing knowledge among project participants and identified how integration could be shifted from information exchange to knowledge exchange. Ontology is a new semantic technology widely adopted in areas such as knowledge engineering, natural language processing, collaborative information systems, and knowledge management. It allows engineers to translate the domain knowledge into a format that machines can understand. Although several ontologies have been proposed to cover various objectives, the majority were developed separately to serve a single objective. A holistic decision-making method that considers various perspectives is required to shift from single- to multi-objective decisions, especially in the preliminary design stages.

#### *2.4.1. Design perspective*

Structural stability is a major element to be considered and verified in the design of any building. The design evaluation relies on data collected from manuals, standards, regulations, and the designer's experience. Due to this study's limited time and resources, it was not possible to explore all types of structures. Columns were selected because they are one of the most critical components in building design and are vital to structural stability. According to Eurocode 2 standards [32], the ultimate axial load capacity of the concrete column needs to be greater or equal to the axial load applied to ensure the feasibility of this design element.

To calculate the ultimate axial load capacity of the concrete column, the concrete load capacity and reinforcement load capacity need to be considered. Consequently, the ultimate axial load capacity will be the sum of both. This equation can be represented as follows:

$$N_{ed}\ (\text{ultimate axial load capacity}) = 0.567 \times \mathrm{Ac} \times \mathrm{fck} + 0.87 \times \mathrm{As} \times \mathrm{fyk}$$

$$\mathrm{Ac} = \mathrm{Ag} - \mathrm{As}$$

$$\mathrm{Ag} = \mathrm{Width} \times \mathrm{Length}$$

$$\mathrm{As} = \left[3.14 \times \left(\mathrm{D}^2/4\right)\right] \times \text{no of bars}$$

Ac = Total net area of column cross-section
Ag = Total gross area of a column
As = Total area of the longitudinal reinforcement
fck = Concrete characteristic strength
fyk = Reinforcing bar characteristic yield strength

On the other hand, some design conditions are not based on equations. They are represented as statements, tables, or charts. This check is usually performed manually, which can be time-consuming because engineers need to retrieve this information from design codes. This can result in mistakes because it relies on human judgment and experience. Consequently, those conditions need to be converted into a machine-readable statement. For instance, to consider fire resistance requirements in a concrete column design, the minimum width of the column and the minimum concrete cover need to be considered. According to Eurocode 2 standards [32] (Table 2), if a column and its cover have minimum widths equal to or greater than 350 mm and 25 mm, respectively, the standard fire resistance per minute is equal to 120. In other words, 2 h of fire resistance requires a 350 mm minimum column size and a 25 mm minimum cover. This condition can be represented as follows:

Environmental restrictions also play a major role in selecting suitable material for a column. According to Eurocode 2 [32], exposure to different elements corrodes and damages the concrete. This includes carbonation-induced corrosion, chloride-induced corrosion, chloride-induced corrosion from seawater, freeze attack, and chemical attack. For different exposure conditions, a minimum strength of concrete needs to be used. For instance, the minimum concrete strength class that can be used if it is exposed to carbonation-induced corrosion is C25/30.

#### *2.4.2. Sustainability perspective*

Sustainability evaluation in building design consists of three main aspects: environmental, social, and economic. These aspects cover factors such as carbon emission, material costs, resource consumption, and worker safety. The user must put significant effort into accessing sustainability data because this information is fragmented among databases in various formats and locations. Current sustainability evaluation tools require a fully detailed design model and this evaluation is usually completed in later design stages. Finding the best possible solution in the preliminary design stages by looking into several factors can significantly influence decision-making.

Research has discovered that the embodied carbon dioxide content in building materials significantly affects the environment. Reducing carbon emissions is linked to the type of materials used in a project. It can affect other factors, such as cost and design safety. In this research, two types of concrete material, regular concrete (NSC) and high-strength concrete (HPC), are evaluated to elaborate on the intended concept. NSC covers C25/30 and C35/45 concrete and HPC covers C80/95 and C90/105. According to BS EN206–1 [33], there are several rules related to the mixing ratio of NSC. Consequently, the mix proportions for the selected concrete were calculated following the available papers and the data were collected from standards. Moreover, HPC has a different mix ratio than NSC. Therefore, the HPC mix ratios suggested by Lim, Yoon and Kim [34] and Larrard and Sedran [35] are considered in this research.

The embodied $CO_2$ for concrete is equal to its components' total embodied carbon contents during production, transportation, and construction. Because this research covers the preliminary design stage, embodied carbon during construction is not considered. Following the equation adapted from Zhang et al. [36] and Yang, Song and Song [37], the embodied $CO_2$ for a concrete type can be calculated as follows:

$$\begin{aligned}\text{Embodied CO2 for concrete} = {} & \text{Embodied } CO_2(\text{production}) \\ & + \text{Embodied } CO_2(\text{transport}) \\ & + \text{Embodied } CO_2(\text{construction}).\end{aligned}$$

Databases were considered [38,39] to calculate the embodied carbon content during production. It supports data for different concrete mix

| |
|---|
| If the ultimate axial load capacity (Ned) is equal to or greater than the axial load applied ➔ then the selected column provides enough strength. |

| |
|---|
| If the minimum column width AND minimum concrete cover are equal to or greater than 350 mm and 25 mm, respectively ➔ then column fire resistance is equal to 120 min |

**Table 3**
$CO_2$ and cost calculation of NSC and HPC concrete reproduced from Zhang et al. [36].

| Item | $CO_{2\text{-}i}$ ($kgCO_2$/kg) | Cost ($US/kg) | Wi(kg/m³) | | | |
|---|---|---|---|---|---|---|
| | | | NSC | | HPC | |
| | | | C25 | C35 | C80 | C90 |
| CEM I 32.5 | 0.930 | 0.22 | 240 | 300 | – | – |
| CEM I 52.5 | 0.476 | 0.25 | – | – | 510 | 580 |
| Aggregate | 0.004 | 0.015 | 1955 | 1915 | 1673 | 1600 |
| Water | 0.0003 | – | 165 | 165 | 165 | 165 |
| Steel | 1.86 | 0.6 | – | – | – | – |
| CO2 (production) ($kgCO_2/m^3$) | – | – | 249 | 286 | 264 | 297 |
| CO2 (transport) ($kgCO_2/m^3$) | – | – | 20 | 20 | 20 | 20 |
| CO2 ($kgCO_2/m^3$) | – | – | 269 | 306 | 284 | 317 |
| Cost ($\$US/m^3$) | – | – | 97 | 95 | 242 | 260 |

ratios, including water usage, unit weight, and embodied carbon content. By using the formula adopted from Yang, Song and Song [37], the embodied $CO_2$ during production can be calculated as follows:

$$\text{Embodied } CO_2 \text{ (production)} = \sum_{i=1}^{n} W_i \text{ x } CO_{2i}$$
$$= 300\text{x}0.93 + 1915\text{x}0.004 + 165\text{x}0.0003$$
$$= 286 \text{ kgCO}_2 \Big/ \text{m}^3$$

For instance, knowing that embodied carbon content ($CO_{2i}$) in the selected cement, aggregate, and water is 0.93 ($kgCO_2$/kg), 0.004 ($kgCO_2$/kg), and 0.0003 ($kgCO_2$/kg), respectively, 300 kg of CEM I 32.5, 1915 kg of aggregate, and 165 kg of water comprise the unit cubic meter of C35 concrete, which equals to 286 $kgCO_2/m^3$ during production. Moreover, the average value of carbon dioxide emissions during material transportation was estimated to equal 20 $kgCO_2/m^3$. Therefore, the embodied $CO_2$ in C35 is equal to 306 $kgCO_2/m^3$. The calculations of the selected concrete are shown in Table 3.

The total embodied carbon content of an element can be calculated as follows:

$$\text{Total Embodied } CO_{2e} \text{ (Element)} = \text{Volume} \times \text{Embodied } CO_{2e} \text{ per unit}$$

The volume of a rectangular element

The volume of the element : Volume = Ac x Height

Weight of the element

Weight of the element : Weight = Density x Volume

### *2.4.3. Cost perspective*

Cost estimation is essential to keep the project within the planned budget. It creates an initial estimate for quantities and materials. Having an initial cost for an element in the design stage facilitates the selection of design alternatives and gives stakeholders a chance to modify the structure. Although the dataset for cost estimates is produced from the architectural model, it may provide only a few data such as space, element area, floor height, building parameter, and gross area [23]. But what if this information is unavailable in the exported IFC-based BIM model? How can the user obtain those data to proceed with their decision? According to Ramaji and Memari [27], information exchange can be divided into direct data exchange, which does not require semantic modifications, and interpreted data exchange, which requires semantic enhancement. Therefore, using ontology and reasoning rules can deduce new information based on existing data. New facts can be deduced even if some information was not included in the exported file. For instance, the area of the element can be calculated based on the embedded rules, which can be used to calculate other information, such as the volume

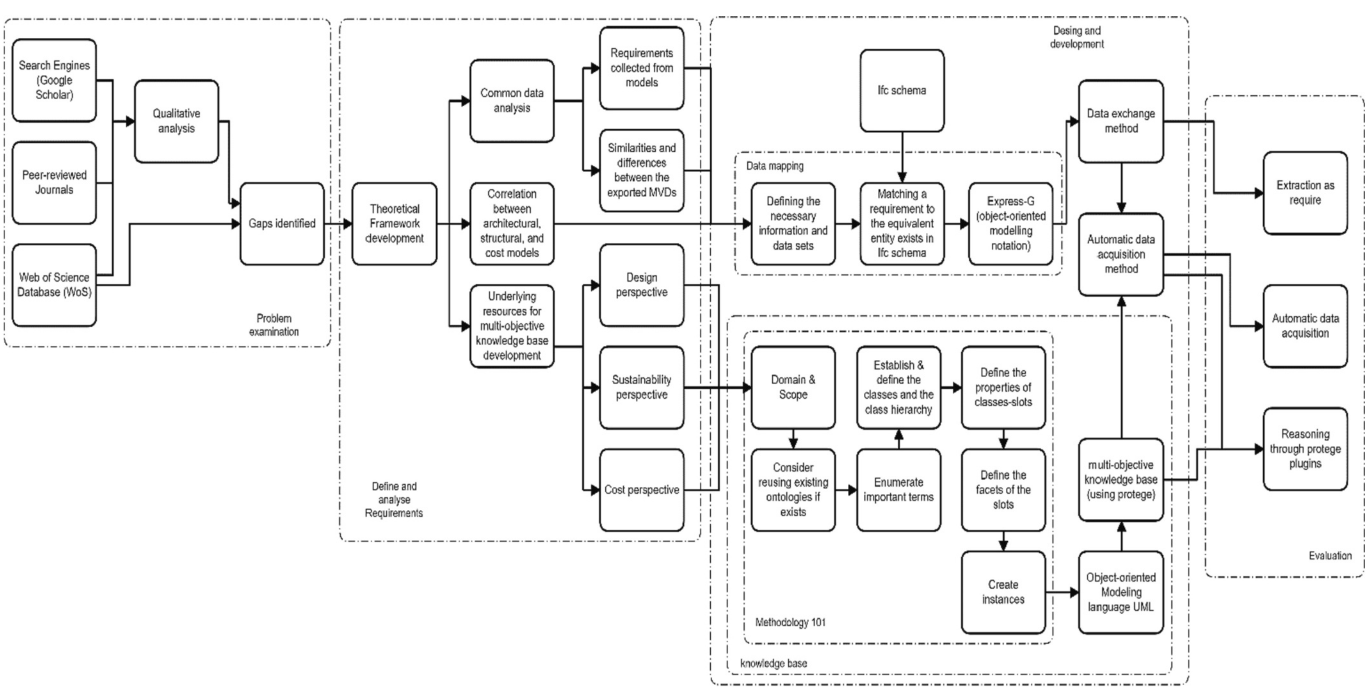



**Fig. 2.** Research methodology.

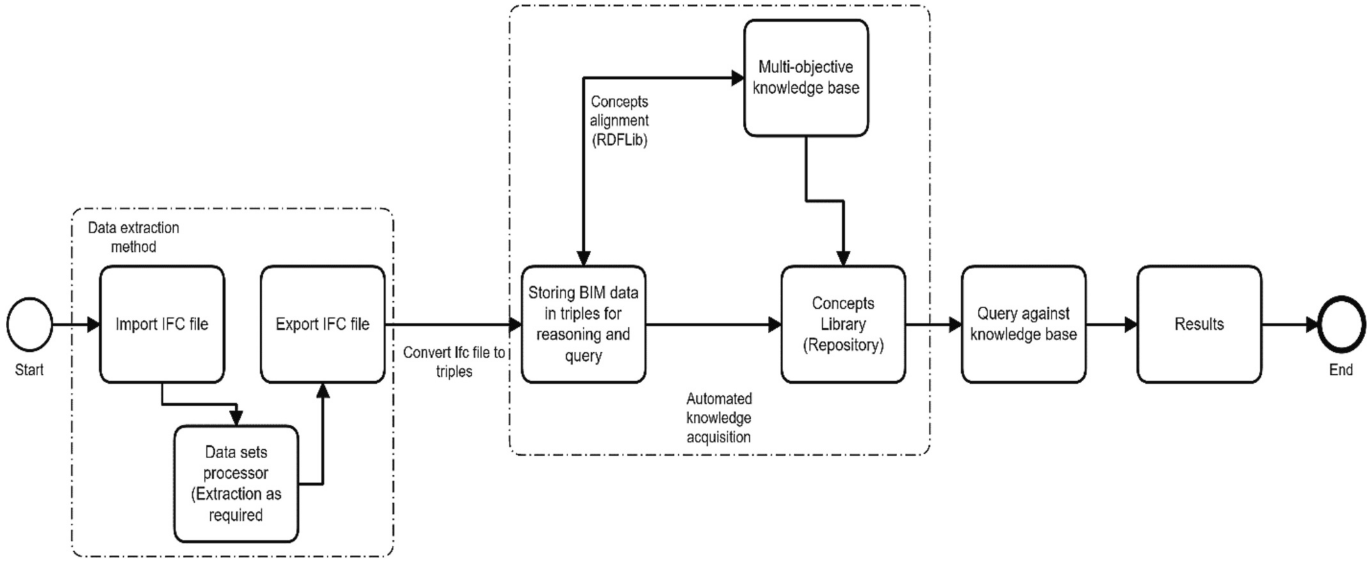



**Fig. 3.** Process map linking both the data extraction tool and the data acquisition method.

and weight of an element.

First, the cost of the concrete material varies based on the concrete's strength. This research will calculate this cost based on the selected concrete material. Second, the required labour cost can be calculated based on the quantities, including concreting work, reinforcement work, formwork, and task duration. Gokce and Gokce [40] calculate the total cost by multiplying the total quantity of each functional element by the unit cost of each functional element. The volume of the element is multiplied by the cost per cubic meter of the material. This can be represented as:

$$\text{Total Cost of material} = \text{volume} \times \text{Cost per unit}$$

Further, estimating the total labour costs during construction early in the design stage can improve project management, which significantly affects the project's budget. However, labour costs are often defined by labour skills, which are different from the cost of materials provided by suppliers [41]. It is important to develop a knowledge base that can model labour costs and consider this aspect in the design stage. In this research, the total labour cost of a column is calculated by the labour costs of column concreting, column reinforcement, and column formwork. First, the labour cost of column concreting includes two main factors: the total volume of concrete, which is calculated based on the section's dimension, and the worker's pay rate. This is represented as follows:

$$\begin{aligned}&\text{The labour cost of column concreting ()}\\&\quad = \text{Total volume of concrete in } \left(\text{m}^3\right) \times \text{payrate of a worker per m}^3\end{aligned}$$

Second, the labour cost of reinforcement used in a column needs to be determined. This is calculated by considering the total weight of steel bars and the worker's pay rate worker. The weight of steel bars can be computed by multiplying the density of steel material (7850 kg/m$^3$) by the total volume of the longitudinal reinforcement. This is calculated as follows:

$$\begin{aligned}&\text{The labour cost of column reinforcement}\\&\quad = \text{Total weight of steel bars in } kg \times \text{payrate of a worker per } kg\end{aligned}$$

$$\text{Volume of steel bars} = \text{As} \times \text{Height}$$

$$\text{Total weight of steel bars} = \text{Density steel} \times \text{Volume of steel bars}$$

Finally, the labour cost of column formwork can be estimated by multiplying the total area of the column formwork used by the worker's pay rate. The total area of column formwork can be calculated by considering the width, length, and height of the column. This is represented as:

$$\begin{aligned}&\text{The total area of shuttering work } \left(\text{m}^2\right)\\&\quad = [\,2 \times (\text{area of width side}) + 2 \times (\text{area of length side})\,]\\&\quad = [\,2 \times (\text{width side} \times \text{height}) + 2 \times (\text{ length side} \times \text{height})\,]\end{aligned}$$

$$\begin{aligned}\text{The labour cost of column formwork} &= \text{Total area of column formwork in m}^2\\&\quad \times \text{payrate of a worker per m}^2\end{aligned}$$

Consequently, the total labour cost of a column is represented as follows:

$$\begin{aligned}\text{The total labour cost of a column} &= \text{labour cost of column concreting}\\&\quad \times \text{labour cost of column reinforcement}\\&\quad \times \text{labour cost of column formwork}\end{aligned}$$

## 3. Research methodology

Because this research is implemented in the information technology research domain and required a mixed method to reach the objectives, the Design Science Research (DSR) was selected, which is used for categories of artefacts in engineering and computer science disciplines to solve a generic challenge experienced in practice [42]. The methodology, Fig. 2, comprises several steps: problem examination, requirements definition, design and development, demonstration, evaluation, and communication.

### 3.1. Problem examination

The problem, challenges, and related research were reviewed and investigated in Sections 1 and 2, which identified that data exchange still faces interoperability issues due to inconsistency in defining data exchange requirements. Although several attempts have been made, there is still a lack of homogeneity, especially because the flexible nature of the IFC schema leaves room to map the same information in different ways. Moreover, having a high-performance building within a project's budget requires the engagement of diverse aspects such as sustainability, cost analysis, and energy performance. Despite the effort to develop a

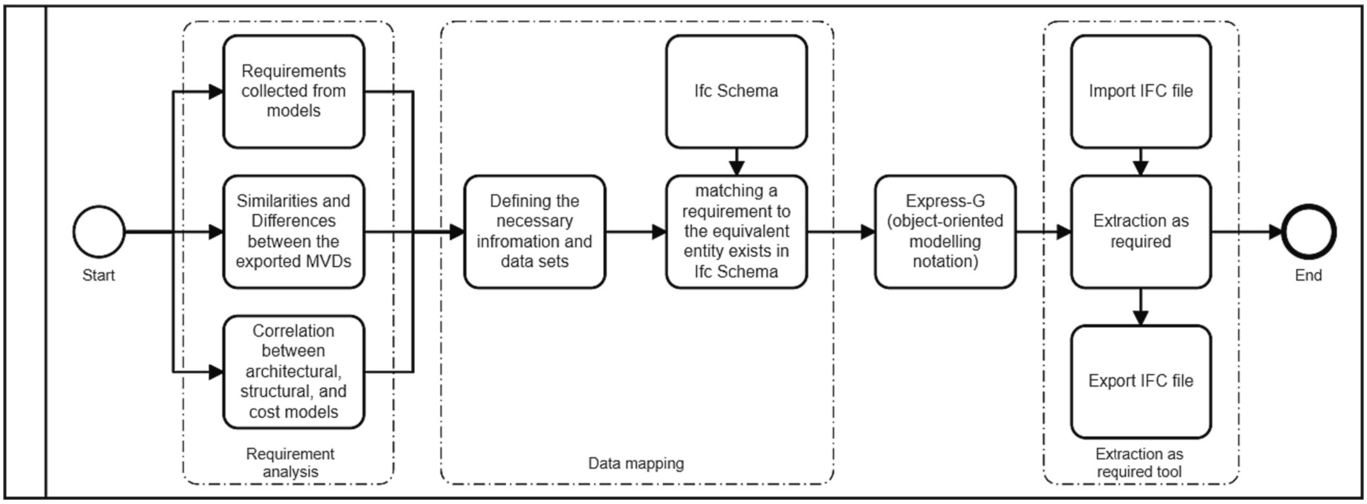



**Fig. 4.** Workflow of the development process of the data exchange method.

multi-objective knowledge base, most of the research did not provide a technique that can work in parallel with a BIM model that can provide decisions based on data collected from the IFC-based BIM model automatically. Most of the knowledge bases were developed separately to serve discrete decisions and required manual input to process the data in a BIM model. Furthermore, software tools require unambiguous clarity in the semantics to allow stakeholders to proceed with their design tasks, and IFC was not designed to deduce new information from a BIM model. It needs to be supported by additional formats to enhance its performance. Consequently, using technologies such as ontology can support BIM models with a multi-objective decision-making method to improve interoperability.

### *3.2. Define and analyze requirements*

This step was divided into several sub-steps to define the required information within the stated context. First, a common data analysis (CDA) referencing concepts such as the IDM method, MVD, and the semantic intersection was designed in a previous publication [14] to understand for each profession what data is required and what information needs to be exchanged to conclude "single truth of information" and "partial truth of information" datasets that form the basis for an exchanging framework from a data perspective. Several BIM models were examined from a data perspective and the expected resolution was evaluated. The design requirements and data needed to support a multi-objective knowledge base incorporating investigated aspects (Section 2.4). The findings in the "Define and analyze requirements" step are the foundation for implementing the proposed framework.

### *3.3. Design and development*

This paper aims to eliminate inefficiencies in data sharing and improve decision-making in the early design stage by proposing a Knowledge-based automatic OpenBIM data exchange framework that combines a data exchange method and semantic web technology. Based on the CDA conducted in a previous publication by Khudhair et al. [14], data exchange was implemented using IfcOpenShell, which is an open-source software library that helps users and software developers work with the IFC file. After the datasets were extracted and saved in the appropriate IFC format, the framework converted the exported IFC file into triples using a semantic web approach, Python, and IfcOpenShell (Fig. 3).

In the meantime, a multi-objective knowledge base was designed. Protégé, which is an open-source ontology editor and framework for building intelligent systems, was used to design and edit the proposed ontology. The converted IFC file triples were further aligned with the proposed multi-objective knowledge base using a data acquisition method that was developed in this research. This method was implemented using RDFLib, which is a Python library for RDF files.

### *3.4. Evaluation*

Scenario-based case testing was carried out on an airport BIM model to validate the research framework. The data exchange method was tested and evaluated by applying it to the airport model to check consistency and ensure no data loss. The developed knowledge base was evaluated first through Pellet, a reasoner plugin within Protégé, to ensure it was syntactically correct and there were no inconsistencies. This testing was done to check whether the automatic data acquisition method could interpret the developed ontology and align it with the IFC data without any inconsistencies. Ontology development 101 [43] was selected to build the proposed ontology because it provides simple guidelines for ontology implementation that inexperienced developers and users can understand.

Further explanation of the development steps is in Section 5. The validation was done in two stages: before and after applying the data acquisition method to ensure the ontology was still semantically and syntactically correct. This validation influenced the knowledge development phase because it ensured that the terms and concepts used were uniform and consistent throughout the ontology development. Second, the framework's efficiency was checked to ensure it provided a multi-objective knowledge base that considered single to multi-objective decisions and worked with different information sources from diverse standards and databases. The SWRL rules were tested by processing several queries to show the proposed framework's reliability in providing multi-objective decisions and new information that was not covered in the exported model.

## 4. Data exchange method using minimum common data set

In this section, the data exchange method was implemented, which includes several stages: (1) identifying all the required data, which was discussed in previous work [14]; (2) mapping the required data to a machine-readable format (Section 4.1), for which the IFC4 schema was selected; and (3) reusing existing libraries to develop an "extraction as required" tool (Section 4.2). The workflow of this section is shown in Fig. 4.

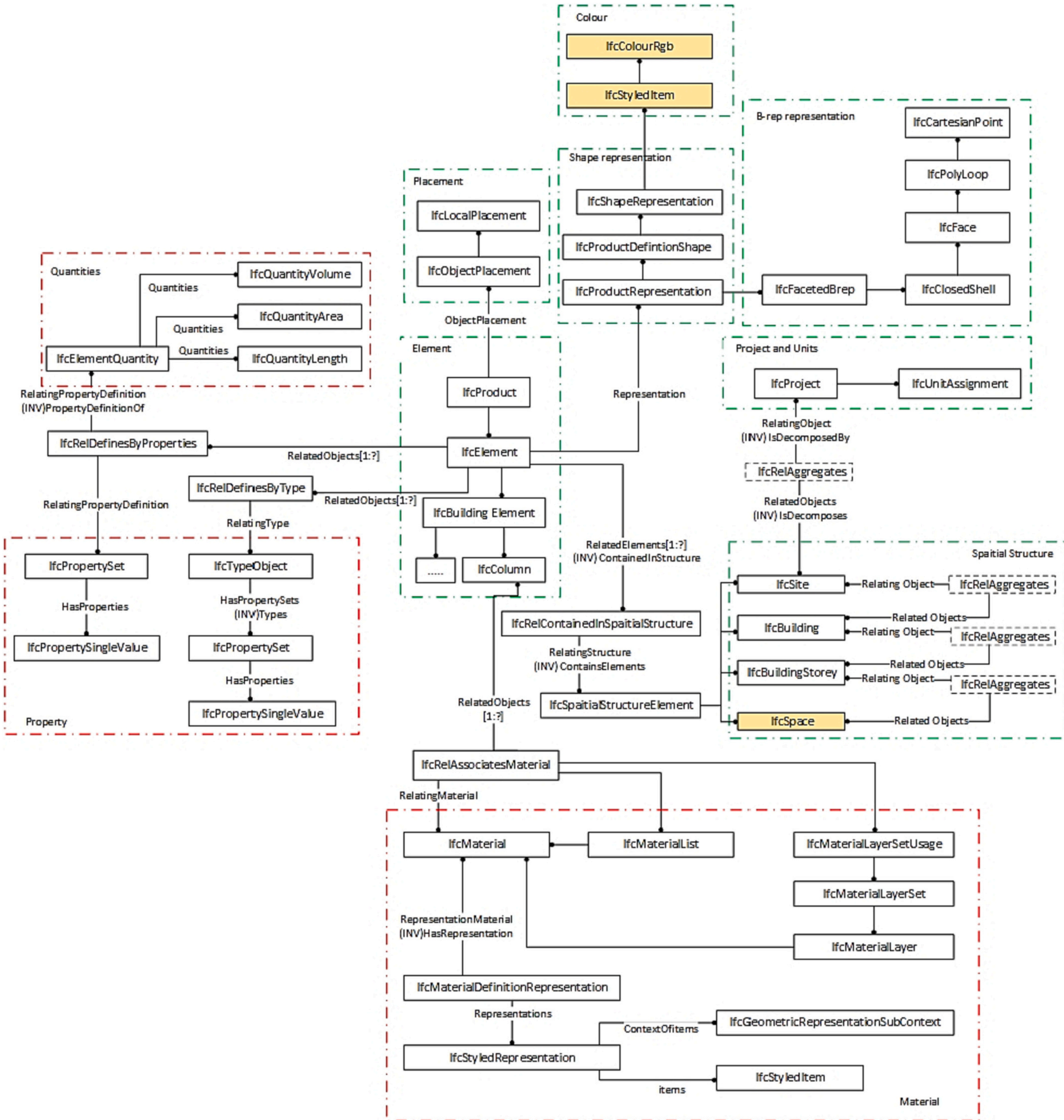



**Fig. 5.** Data sets representation in IFC schema using EXPRESS–G.

### 4.1. Mapping requirements to a machine-readable format

The collected information was used to map the defined requirements to the IFC schema. A requirement is matched to its equivalent entity in a given schema. This process can differ from one developer to another. However, defining a minimum common data set enables developers to use the same mapped data set when they create their idea. They can then extend it to fit their specific use case, eliminating the time wasted. This section uses structural and cost information as an example.

An object-oriented modelling notation approach based on Express-G, a graphical modelling language used for object-oriented information modelling, was used to map the defined requirements to the IFC data structure and draw the relationships among them. Fig. 5 illustrates entities that are related to different models. Some of these entities are common among several models. A green dotted box marks this common information. For instance, project data and units are common information required by all disciplines. The IfcProject entity is used to contain project data and the units in the project.

The spatial structure delivers the project structure to form a building and is significant in constructing the hierarchical composition in an IFC file. Entities contained by the spatial structure are IfcSite, IfcBuilding, IfcBuildingStorey, and IfcSpace [44], while the IfcRelAggregates

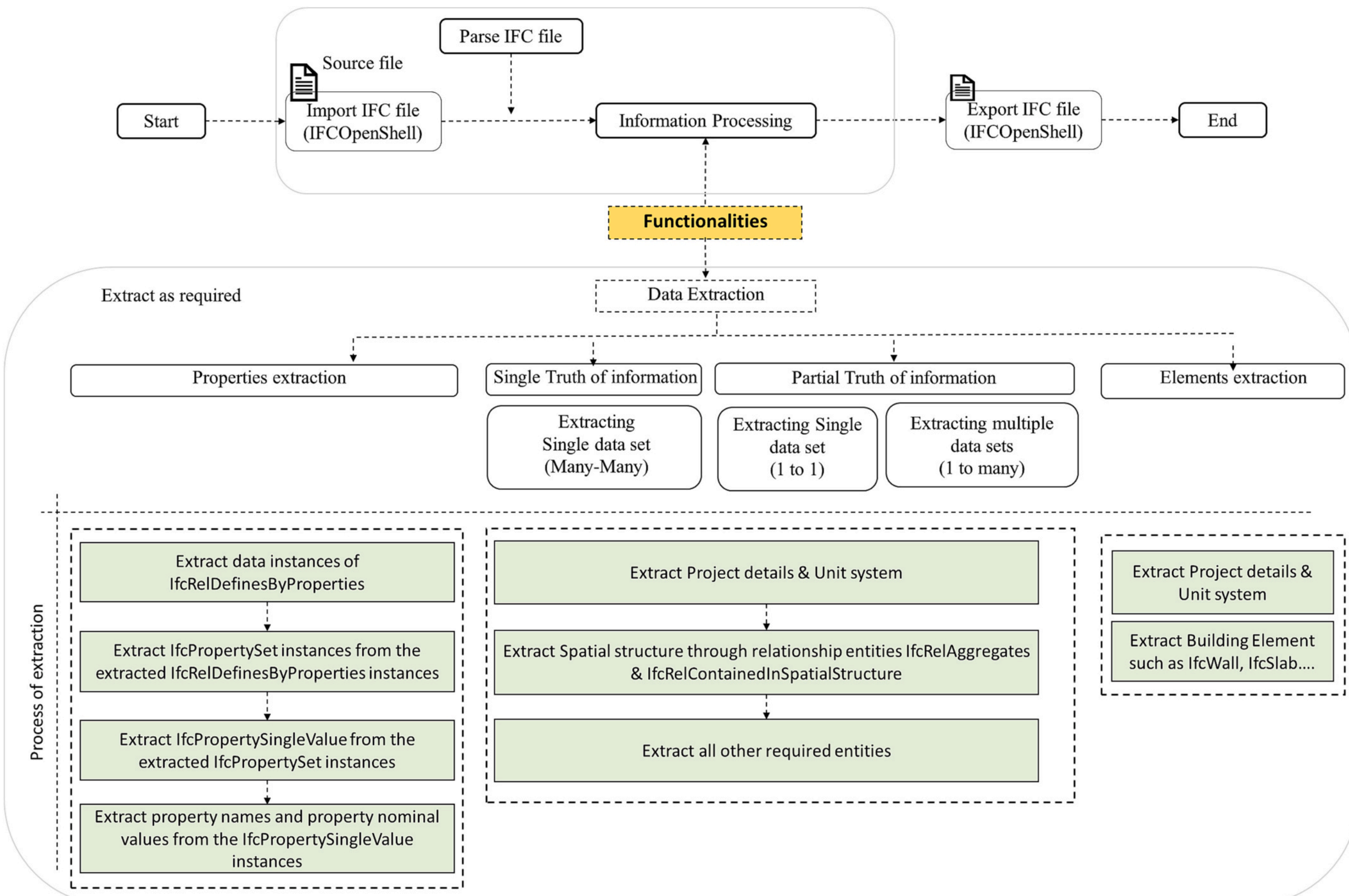



**Fig. 6.** The workflow of the data extraction tool.


**Fig. 7.** An example of using the developed tool to extract IfcRelAggregates entities.

relation entity shows the relation among them [44], and the IfcRelContainedInSpatialStructure relates elements to spatial structure [44]. For instance, it relates IfcElement, such as IfcColumn, to IfcBuildingStorey. Consequently, all these entities are commonly shared by all datasets except for IfcSpace, which can depend on the use case. To indicate it was an optional entity, it was represented by a yellow box in Fig. 5.

Furthermore, the position and dimensions of an element are determined with the IfcObjectPlacement, which is provided for an object with IfcProductDefinitionShape as shape representation [45]. A subtype entity inherits the attributes from its supertype. For instance, IfcProductDefinitionShape is a subtype of IfcProductRepresenation. Hence, all the Information in IfcProductRepresenation will be assigned to IfcProductDefinitionShape automatically. The shape information is necessary for visualization and can be used to infer new information, such as area and volume, by taking the dimensions of an element as input. Consequently, all these entities are commonly shared because those dimensions will be used later in this research to provide embodied carbon content and cost in a given element.

In contrast, other entities are related more to a specific domain. In this research, these entities represent some of the structural and cost estimation information. For instance, IfcPropertySet is used to hold properties within a property tree. Building elements are linked to their properties following two paths: direct link using IfcRelDefinesByProperties and indirect link using IfcRelDefinesByType [44,46]. These entities relate an element to a property set (IfcPropertySet) and an element type (IfcTypeObject). Using the IfcRelDefinesByProperties relationship entity, the IfcWall entity can relate to an instance of IfcPropertySet. In the cost model, IfcElementQuantity is used to obtain properties such as length (IfcQuantityLength), area (IfcQuantityArea), volume (IfcQuantityVolume), and others. To relate this entity to the elements, IfcRelDefinesByProperties is used. These entities are identified as discipline-specific information and marked with red dotted boxes because they can hold values related to a specific scenario. Furthermore, IfcElementQuantity is not always provided in an IFC file. The imported model might not present values for the length, area, and volume. In this research, those values will be calculated by applying SWRL rules in case they do not exist in the imported file.

### 4.2. Extraction using IfcOpenShell library

The initial functionalities required by any data extraction tool are to read and analyze the IFC schema, also known as an IFC parser functionality, to process information, which can be divided into several sub-functionalities, such as extracting groups of datasets (one-to-one, one-to-many, and many-to-many); to extract only a specific type of data out of a group of datasets, such as element extraction; and to extract a property set, which includes extracting the properties related to a specific element or a group of elements.

#### 4.2.1. Reading and parsing the IFC schema

Automating the data exchange comprises two aspects: the IFC parser, which is used to read the IFC physical file, and the IFC model schema, which is used to create the equivalent objects in a machine-comprehensible format. Several efforts have focused on developing open-source libraries for software developers to work with IFC files. This paper selected the IfcOpenShell library to implement the data exchange method, and the library's uninterrupted progress allows the developers to add more functionalities and update the tool based on the new IFC4 schema.

#### 4.2.2. Information processing

The workflow was divided into three parts (Fig. 6).

(1) Extraction was performed as required, including extraction of single or multiple datasets. This extraction included several objects according to their types and related entities. For instance, classes such as Structuraldataset() and Costdataset()were created based on the defined requirements to extract various datasets. These datasets were used to extract a partial model from the imported model.

To achieve extraction, the relationship entity was included to extract datasets. This approach extracted a group of instances because these entities were defined and used in the IFC schema to specify the relations across different entities in an IFC model. For instance, to extract data related to project details and spatial structure, the IFC relation entities IfcRelAggregates and IfcRelContainedInSpatialStructure were used. Fig. 7 illustrates an example of the extraction of IfcRelAggregates and its related data instances. The data instances with the identifier (ID) numbers #1033759, #1033763, and #1033767 are instances of IfcRelAggregates. These instances included the data instances of IfcProject (#108), IfcSite (#1030319), IfcBuilding (#123), and IfcBuildingStorey (#148 and #166). Considering the IFC files were modelled differently, each has been added separately. This approach was used only in the partial model extraction function and cannot be used for element extraction because it will extract data that might not be needed.

The building members were represented as IfcColumn, IfcSlab, and IfcWall. This representation was different in the structural analysis model. The building members were represented as IfcStructuralCurveMember for linear elements such as Column and IfcStructuralSurfaceMember for surface elements such as Wall and Slab. The requirements for the structural model and the structural analysis model were combined to form one model based on Ramaji and Memari's work [27]. They stated that following this extraction process will link the physical design model to its analytical model. Therefore, an entity, such as IfcStructuralAnalysisModel, used to assemble all information needed to represent a structural analysis model [44] was included. It comprised a structural element, structural connection, and structural activities.

(2) Element extraction can either extract the instance or eliminate unnecessary instances. Although it is possible to acquire an element directly, extracting it immediately without its spatial structure can result in inconsistency in the IFC file hierarchy. In this extraction step, only the required element with its spatial structure and project details were retained.

(3) Property set extraction was used to extract property data sets and quantity sets that can be used as input data for design needs. As previously explained, building elements are linked to their properties following two paths: direct link using IfcRelDefinesByProperties and indirect link using IfcRelDefinesByType. The proposed method uses IfcElement to find the IfcRelDefinesByProperties using the path: IfcRelDefinesByProperties $\geq$ IfcPropertySet. This iteration will reach IfcPropertySingleValue, which includes name, description, nominal value, and unit of elements. The relationship entity can be extracted using the inverse (INV) attribute IsdefinedBy, whereas the related entity can be extracted using the direct attribute RelatingPropertyDefinition. The algorithm uses the same workflow to extract quantities; however, quantities are found using the path IfcRelDefinesByProperties $\geq$ IfcElementQuantity, which includes area, volume, and length.

## 5. Ontology development and data acquisition method

This section discusses developing and implementing the multi-objective knowledge base and the automatic data acquisition method. Protégé was used to model, edit, and work with the ontology. It has several plugins, some of which were used in this research, including Semantic Web Rule (SWRL), which deduces new facts based on existing information and Query-Enhanced Web Rule Language (SQWRL), which allows end users to query required information. In addition, the reasoning plugin Pellet was used to check the consistency of the

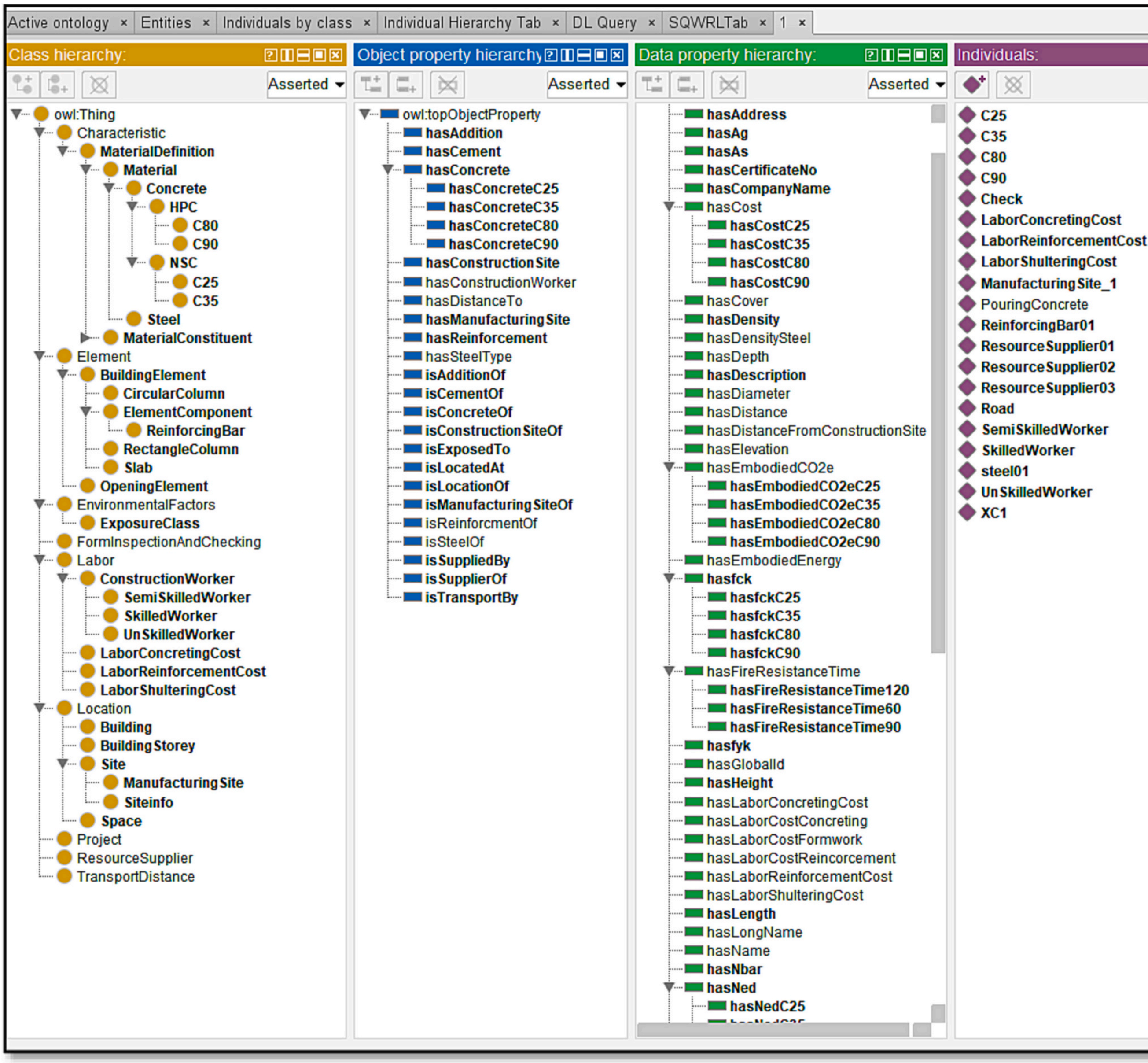



**Fig. 8.** The proposed ontology in Protégé before applying the data acquisition method.

developed knowledge base before and after applying the data acquisition method. The data collected were stored as classes, properties, relations, instances, rules, and values. The output of the ontology can be delivered in OWL/XML or RDF format. RDFLib, which is based on RDF, will be used later to develop the automatic data acquisition method. Ontology development 101 [43] was selected to build the knowledge base. This method requires several steps.

- *Domain and scope.* This step is critical to the ontology development phase because ontology development covers broad topics and domains. The proposed ontology aims to provide a holistic decision-making knowledge base to assist engineers who lack knowledge associated with sustainability and cost to compare design choices and conditions based on existing data to develop an ideal design in the early design stage.
- *Consider reusing existing ontologies.* Using existing ontologies can facilitate the development of ontologies that are compatible with one another. The developed ontology is semantically valid by default because the existing ontologies were developed by other experts and have already been validated. Only the additional concepts need further validation. For instance, the structure of the proposed ontology follows the semantic structure of the IfcOWL ontology, which was created based on the IFC schema.
- *Enumerate important terms and define the class hierarchy.* As previously discussed, the key concepts were obtained from sources in the literature and databases. The collected concepts must be structured in a hierarchy to indicate the relations and attributes. Chong Johnson and Chong Johnson Lim [47] classified the ontology development process into two approaches: top-down and bottom-up. This research uses a top-down approach to create a taxonomy to organize and connect concepts. According to Corcho and Fernandez-Lopez [48], a basic ontology needs to include several elements: (1) classes, which act as a blueprint that reflects the concepts considered; (2) object properties, which represent the relations between concepts; and (3) data-type properties, which represent the relations between concepts and attributes and can be characterized as a string, float, Boolean, or integer. The general classes, including their sub-classes, were added first. For instance, Main classes, such as characteristics, were broken

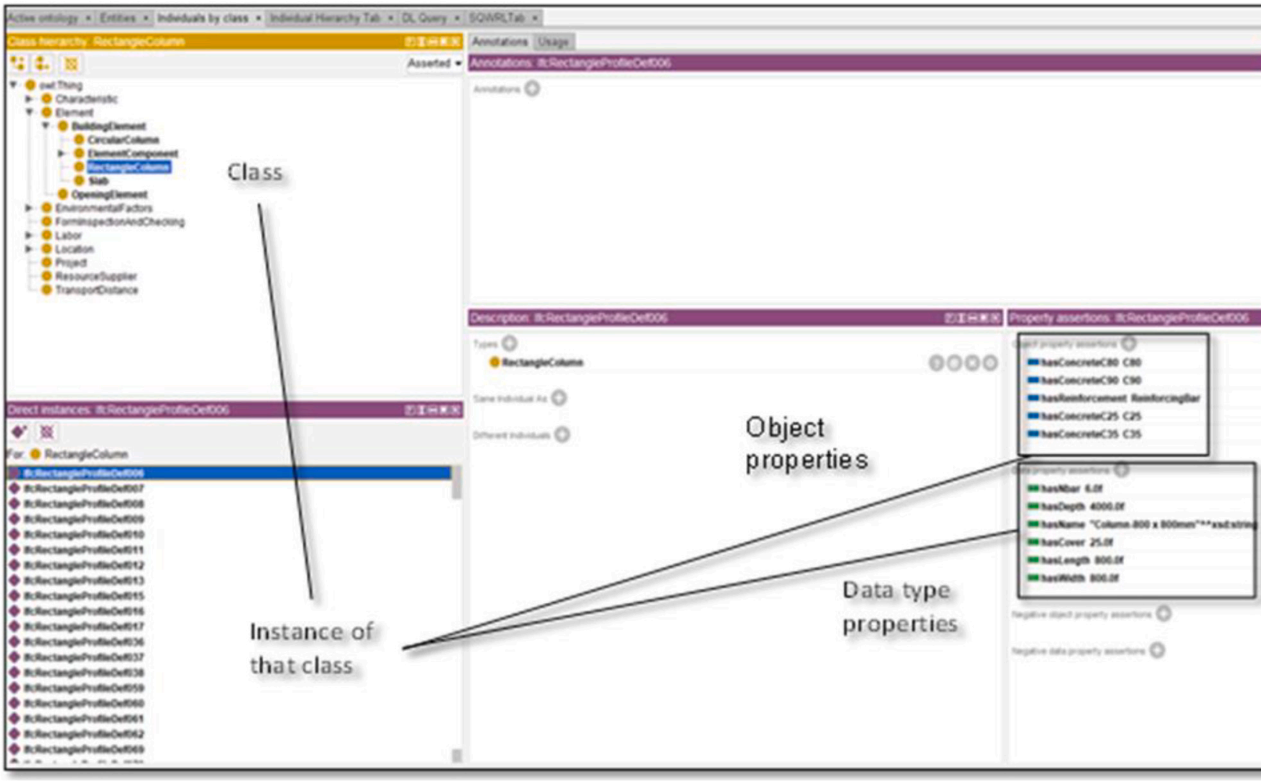



**Fig. 9.** Instances of a rectangular column class in Protégé before applying the data acquisition method.

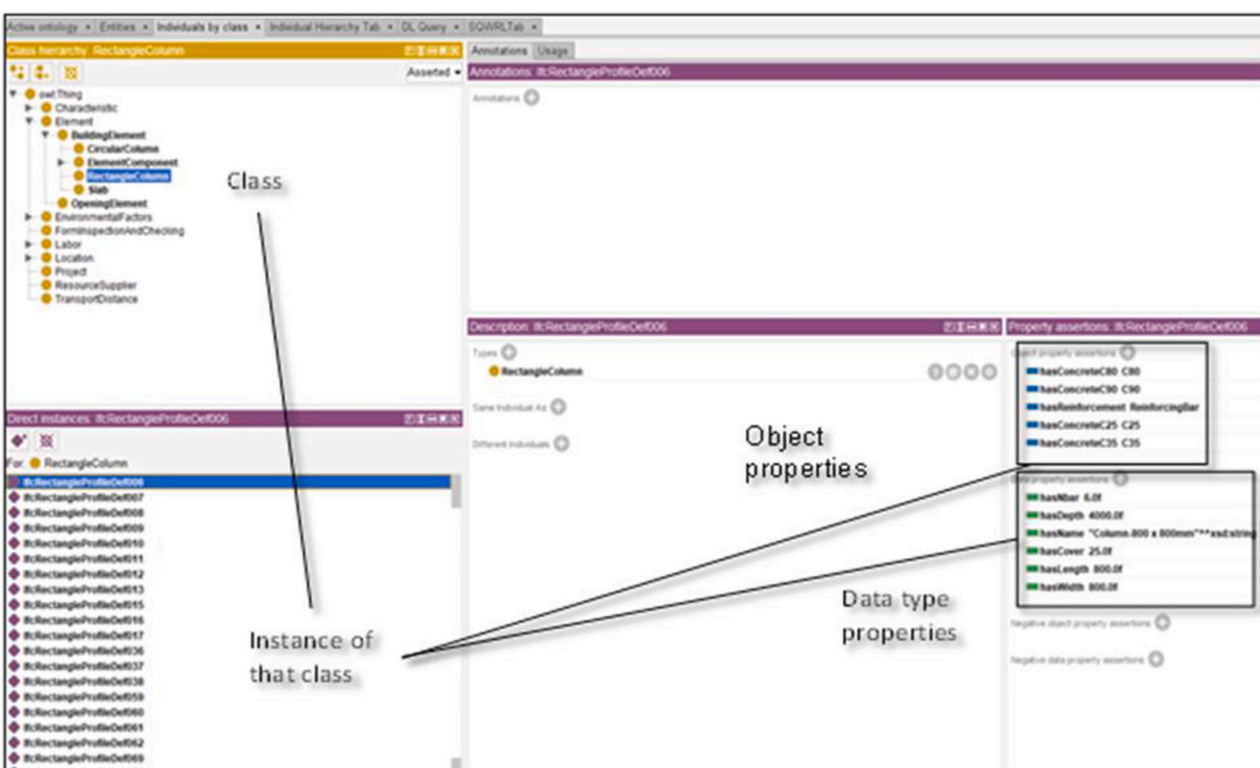



**Fig. 10.** Instances of a rectangular column class in Protégé after applying the data acquisition method.

**Table 4**
Example of SWRL rule.

| |
|---|
| *Rule 1–1: Net cross-section area (Ac) of a rectangular Column* |
| RectangleColumn(?Column) ˆ hasAg(?Column,?ColAg) ˆ hasAs(?Column,?CAs) ˆ swrlb:subtract(?ColAc,?ColAg,?CAs) - > hasAc(?Column,?ColAc) |
| *Rule1–2: Gross cross-section area (Ag) of rectangular Column* |
| RectangleColumn(?Column) ˆ hasWidth(?Column,?Cb) ˆ hasLength(?Column,?Ch) ˆ swrlb:multiply(?ColAg,?Cb,?Ch) - > hasAg(?Column,?ColAg) |
| *Rule1–3:Area of longitudinal reinforcement (As)* |
| RectangleColumn(?Column) ˆ hasNbar(?Column,?CNbar) ˆ ReinforcingBar(?RB) ˆ hasDiameter(?RB,?Diameter) ˆ swrlb:multiply(?CAs,?CNbar,?Diameter,?Diameter, 3.14, 0.25) - > hasAs(?Column,?CAs) |

For the end user, SQWRL was used to query information from the developed ontology. For instance, to query the cross-section area of rectangular columns following the SWRL rules described, the syntax *sqwrl: select* is used, and the following query is built (Table 5).

**Table 5**
Example of an SQWRL query: cross-section area of a rectangular Column.

| |
|---|
| RectangleColumn(?Column) ˆ hasWidth(?Column,?Width) ˆ hasLength(?Column,?Length) ˆ hasAg(?Column,?ColAg) ˆ hasAs(?Column,?ColAs) ˆ hasAc(?Column,?ColAc) - > sqwrl: select(?Column,?Width,?Length,?ColAg,?ColAs,?ColAc) |

down into the material definition class, which was divided into the material class that included concrete types such as HPC and NSC. Other main super-classes included element, labour, location, project, and ResourceSupplier(Fig. 8).

- *Define the properties of classes.* After defining the class hierarchy in all concepts, object property, data-type property, and annotation property are defined. Object property defines the relationship between two classes. For instance, an object property, such as isLocatedAt, can be defined by providing the first class, such as building, as the domain, whereas the second class, such as Siteinfo, can be defined as a range. The data-type property defines the attributes of class instances. For instance, a C25 concrete has compressive strength (hasfckC25), cost (hasCostC25), density (hasDensity), and embodied CO2 (hasEmbodiedCO2eC25). All the defined data-type properties are shown in Fig. 8. The final type is the annotation property, which adds comments or explanations in text format to any property class.

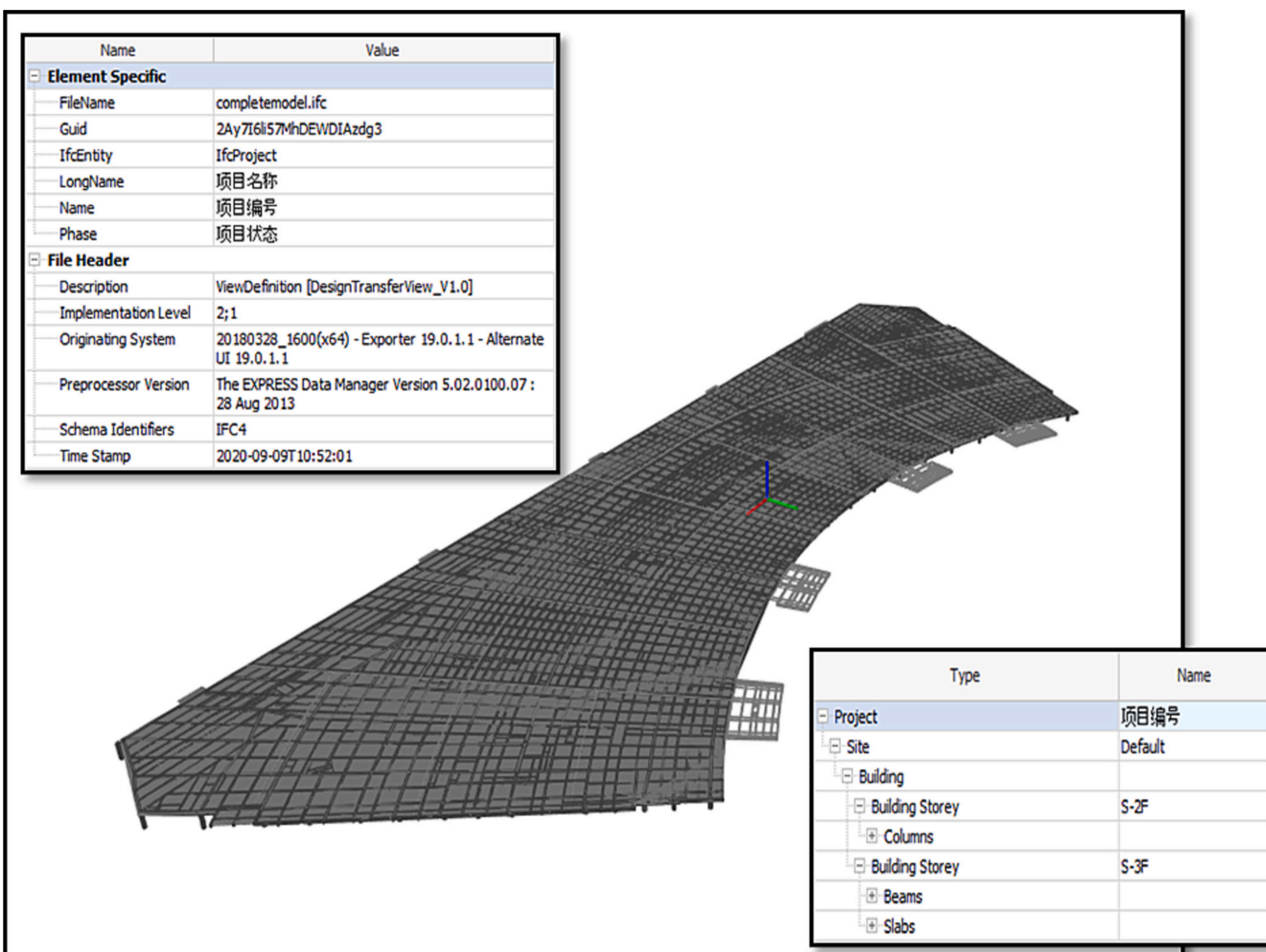



**Fig. 11.** IFC-based Airport BIM model used for the case study.

**Table 6**
Total number of entities before and after data processing.

| File name | Total entities | Building element | Columns | Column type | Beams | Beam type | Slabs | Slab type |
|---|---|---|---|---|---|---|---|---|
| Before extraction | | | | | | | | |
| Original IFC file | 664,280 | 3415 | 424 | 389 | 2962 | 2958 | 29 | 0 |
| After extraction | | | | | | | | |
| Columns-IFC file | 658,331 | 424 | 424 | 389 | 0 | 0 | 0 | 0 |
| Beams-IFC file | 663,438 | 2962 | 0 | 0 | 2962 | 2958 | 0 | 0 |
| Slabs-IFC file | 657,547 | 29 | 0 | 0 | 0 | 0 | 29 | 0 |
| SCDS-str | 659,722 | 3415 | 424 | 389 | 2962 | 2958 | 29 | 0 |
| SCDS-cost | 664,279 | 3415 | 424 | 389 | 2962 | 2958 | 29 | 0 |
| MCDS | 640,872 | 3415 | 424 | 0 | 2962 | 0 | 29 | 0 |

**Table 7**
An example of the SWRL rules and SQWRL queries used to answer Q-a.

*Rule 2–1: Ultimate axial load of a rectangular column (C25)*
RectangleColumn(?Column) ˆ hasAs(?Column,?CAs) ˆ hasAc(?Column,?ColAc) ˆ hasConcreteC25(?Column,?Con) ˆ C25(?Con) ˆ hasfckC25(?Con,?Confck) ˆ ReinforcingBar(?SB) ˆ hasfyk(?SB,?SBfyk) ˆ swrlb:multiply(?x, 0.576,?Confck,?ColAc) ˆ swrlb:multiply(?y, 0.87,?CAs,?SBfyk) ˆ swrlb:add(?CNed,?x,?y) - > hasNedC25(?Column,?CNed)
*Query 2–1: Ultimate axial load of a rectangular column (C25)*
RectangleColumn(?Column) ˆ hasName(?Column,?Name) ˆ hasAs(?Column,?CAs) ˆ hasAc(?Column,?ColAc) ˆ hasConcreteC25(?Column,?Con) ˆ C25(?Con) ˆ hasfckC25(?Con,?Confck) ˆ ReinforcingBar(?SB) ˆ hasfyk(?SB,?SBfyk) ˆ swrlb:multiply(?x, 0.576,?Confck,?ColAc) ˆ swrlb:multiply(?y, 0.87,?CAs,?SBfyk) ˆ swrlb:add(?CNed,?x,?y) ˆ hasNedC25(?Column,?CNed) - > sqwrl:select(?Column,?Name,?ColAc,?CAs,?Confck,?SBfyk,?CNed)

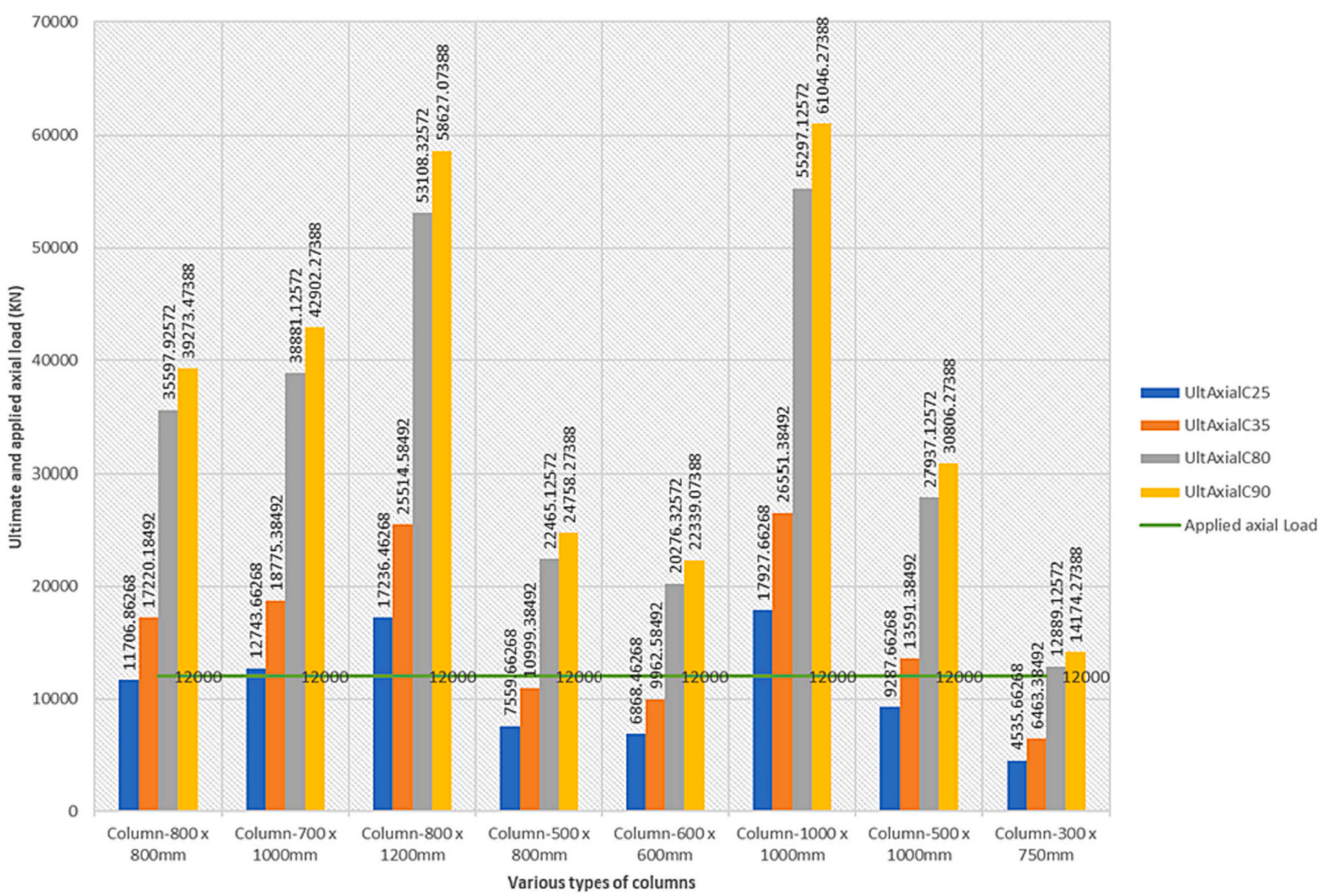



**Fig. 12.** Ultimate load capacity for rectangular columns with various concrete strength.

- *Define the facets and create instances.* Most of the ontologies were produced manually to work as a knowledge base. In work done by Zhang et al. [36], where they developed a multi-objective knowledge base, instances were added manually one by one, which can be time-consuming and requires users to know how to add the needed instances and values to generate results. This provides a static knowledge base, which does not allow the engineers to link to the actual project information to review design choices. In the proposed ontology, the object and data-type properties were added in two steps.

**Table 8**
Ultimate axial load meet design condition (C25).

| |
|---|
| RectangleColumn(?Column) ˆ hasAc(?Column,?ColAc) ˆ hasAs(?Column,?CAs) ˆ hasConcreteC25(?Column,?Con) ˆ C25(?Con) ˆ hasfckC25(?Con,?Confck) ˆ ReinforcingBar(?SB) ˆ hasfyk(?SB,?SBfyk) ˆ swrlb:multiply(?x, 0.576,?Confck,?ColAc) ˆ swrlb:multiply(?y, 0.87,?CAs,?SBfyk) ˆ swrlb:add(?CNed,?x,?y) ˆ swrlb:greaterThanOrEqual(?CNed, 12,000,000) -> meetDesignConditionC25(?Column, “Yes”) |

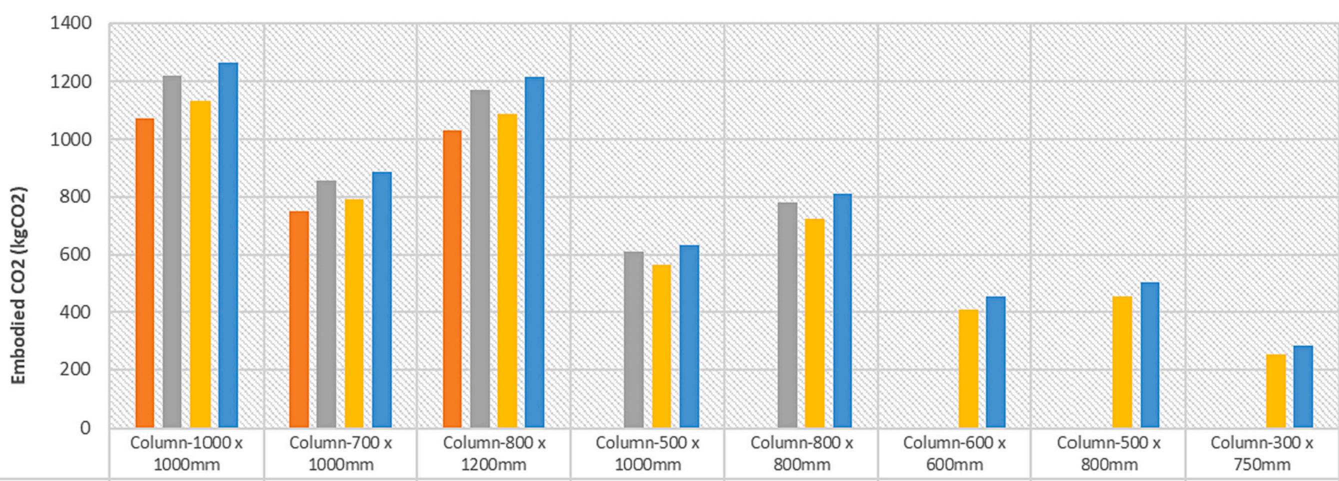
**Table 9**
An example of the SWRL rules and SQWRL queries used to answer Q-b.

| |
|---|
| *Rule7–1: total embodied CO2eC25 while considering design condition* |
| RectangleColumn(?Column) ˆ hasVolume(?Column,?CV) ˆ hasConcreteC25(?Column,?Con) ˆ C25(?Con) ˆ hasEmbodiedCO2eC25(?Con,?ECO2) ˆ swrlb:multiply(?TECO2,?CV,?ECO2) - > hasTotalEmbodiedCO2eC25(?Column,?TECO2) |
| *Q7–1: Total embodied CO2e —C25 while considering design condition* |
| RectangleColumn(?Column) ˆ hasName(?Column,?Name) ˆ hasVolume(?Column,?CV) ˆ hasConcreteC25(?Column,?Con) ˆ C25(?Con) ˆ hasEmbodiedCO2eC25(?Con,?ECO2) ˆ swrlb:multiply(?TECO2,?CV,?ECO2) ˆ hasTotalEmbodiedCO2eC25(?Column,?TECO2) ˆ meetDesignConditionC25(?Column, “Yes”) ˆ hasNedC25(?Column,?CNed) - > sqwrl:select(?Column,?Name,?CV,?Con,?CNed,?ECO2,?TECO2) |

(1) The first step occurs before the data acquisition method is applied and represents static knowledge that includes information collected from manuals, papers, databases, and standards. The collected values are fixed but might change after a period of time. These instances were added by selecting the specific class and instances, including their properties.
(2) The second step, which represents dynamic knowledge, is performed using the automatic data acquisition method by RDFLib and IfcOpenShell, where additional properties are added based on the data collected from the IFC file. These instances and information will change according to the project (IFC file). This approach will eliminate manual input and connect with project data.

The alignment is normally performed by comparing and mapping the concepts based on the ontology structures and the linguistic similarity among concepts. By using RDFLib, the developed method takes the original ontology, including its classes, properties, instances, and rules, as input and generates a new file in RDF format. In the meantime, IfcOpenShell goes through the IFC structure, extracts the required values from the imported IFC file, and assigns them to the correct Uniform Resource Identifier (URI) using RDFLib. For instance, the RectangleColumn class (Fig. 9) showed no instances before the data acquisition. By iterating through the IfcColumn entity, several instances were added under the RectangleColumn class (Fig. 10). These instances were extracted and aligned through the IfcRectangleProfileDef entity and by using the URI.

Each instance consists of object properties and data-type properties. For example, the column and profile names have been assigned automatically to each IfcRectangleProfileDef instance using the hasName and ProfileName data-type properties, respectively. Other data-type property values, such as length (hasLength) and width (hasWidth),




| | Column-1000 x 1000mm | Column-700 x 1000mm | Column-800 x 1200mm | Column-500 x 1000mm | Column-800 x 800mm | Column-600 x 600mm | Column-500 x 800mm | Column-300 x 750mm |
|---|---|---|---|---|---|---|---|---|
| TEmbodied25 | 1073.972816 | 751.172816 | 1030.932816 | | | | | |
| TEmbodied35 | 1221.693984 | 854.493984 | 1172.733984 | 609.693984 | 781.053984 | | | |
| TEmbodied80 | 1133.859776 | 793.059776 | 1088.419776 | 565.859776 | 724.899776 | 406.819776 | 452.259776 | 253.459776 |
| TEmbodied90 | 1265.611088 | 885.211088 | 1214.891088 | 631.611088 | 809.131088 | 454.091088 | 504.811088 | 282.911088 |

**Fig. 13.** Comparison of total embodied CO2 of different concrete with respect to the selected columns while considering design condition (load capacity).

**Table 10**
An example of the SWRL rules and SQWRL queries used to Q-c.

| |
|---|
| *Rule9–1: total cost of square columnC25* |
| RectangleColumn(?Column) ˆ hasVolume(?Column,?CV) ˆ hasConcreteC25(?Column,?Con) ˆ C25(?Con) ˆ hasCostC25(?Con,?Cost) ˆ swrlb:multiply(?TCost,?CV,?Cost) - > hasTotalCostC25(?Column,?TCost) |
| *Q9–1: total cost of columnC25* |
| RectangleColumn(?Column) ˆ hasName(?Column,?Name) ˆ hasVolume(?Column,?CV) ˆ hasConcreteC25(?Column,?Con) ˆ C25(?Con) ˆ hasCostC25(?Con,?Cost) ˆ hasTotalCostC25(?Column,?TCost) ˆ meetDesignConditionC25(?Column, “Yes”) ˆ hasNedC25(?Column,?CNed) - > sqwrl:select(?Column,?Name,?CV,?Con,?CNed,?Cost,?TCost) |

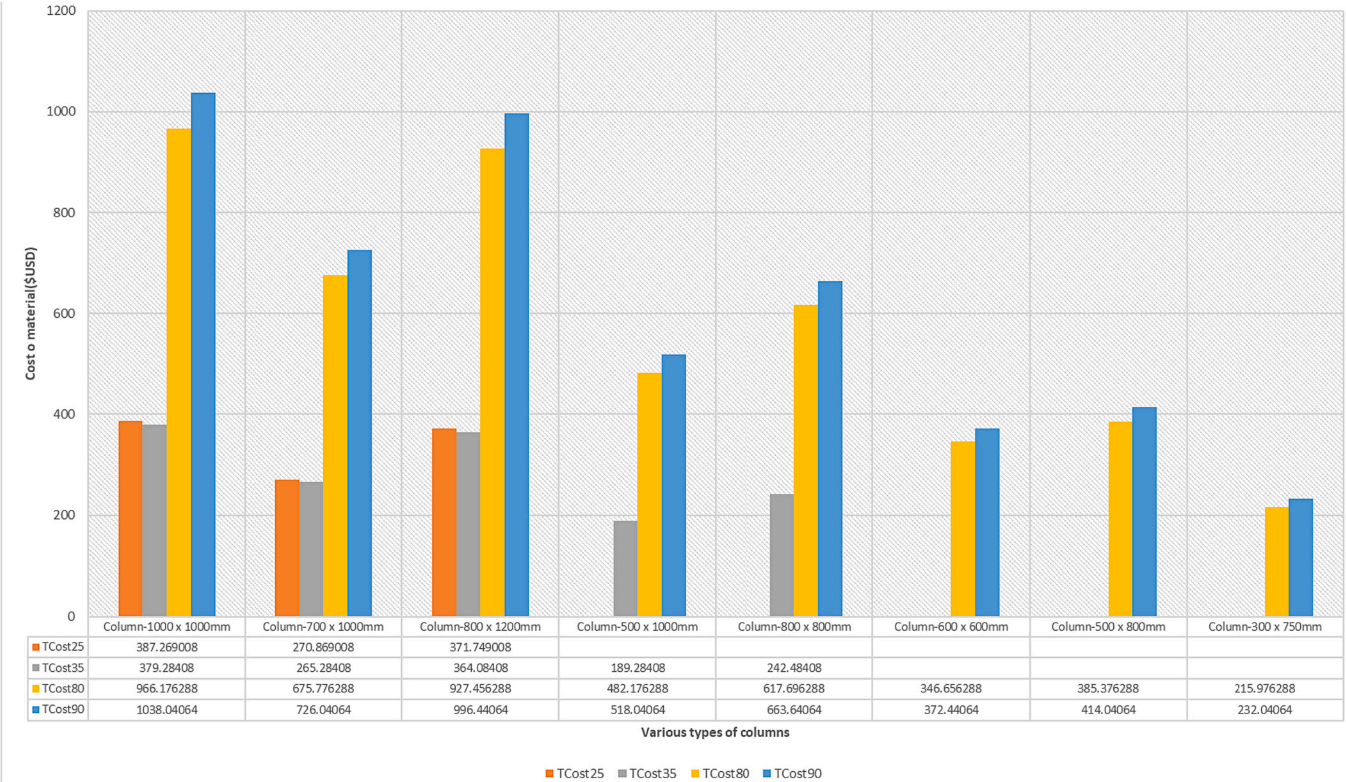



**Fig. 14.** Comparison of the material cost of different concrete with respect to the selected columns while considering design conditions.

**Table 11**
Some of the SWRL rules used to answer Q-d.

| |
|---|
| *Rule11–1: Labour Cost rectangular column Concreting* |
| RectangleColumn(?Column) ˆ hasVolume(?Column,?CV) ˆ LabourConcretingCost(?LabourConCost) ˆ hasLabourConcretingCost(?LabourConCost,?hasLabourConCost) ˆ swrlb:multiply (?LCC,?CV,?hasLabourConCost) - > hasLabourCostConcreting(?Column,?LCC) |
| *Rule11–2: Labour Cost rectangular column Reinforcement* |
| RectangleColumn(?Column) ˆ hasWeightSteel(?Column,?WS) ˆ LabourReinforcementCost(?LabourReinfCost) ˆ hasLabourReinforcementCost(?LabourReinfCost,?hasLabourReinfCost) ˆ swrlb:multiply(?LCR,?WS,?hasLabourReinfCost) - > hasLabourCostReincorcement(?Column,?LCR) |
| *Rule11–3: Labour Cost rectangular column formwork* |
| RectangleColumn(?Column) ˆ hasTotalAreaShulteringWork(?Column,?TASHW) ˆ LabourShulteringCost(?LabourShultCost) ˆ hasLabourShulteringCost(?LabourShultCost,? hasLabourShultCost) ˆ swrlb:multiply(?LCF,?TASHW,?hasLabourShultCost) - > hasLabourCostFormwork(?Column,?LCF) |

**Table 12**
Some of the SWRL rules used to answer Q-d.

| |
|---|
| *Rule11–4: Total Labour Cost rectangular column* |
| RectangleColumn(?Column) ˆ hasLabourCostConcreting(?Column,?LCC) ˆ hasLabourCostReincorcement(?Column,?LCR) ˆ hasLabourCostFormwork(?Column,?LCF) ˆ swrlb:add(? TotalLCC,?LCC,?LCR,?LCF) - > hasTotalLabourCostColumn(?Column,?TotalLCC) |

were added following the same process. Bearing in mind that All calculations are made with a depth equal to 4 m, representing the column's height.

- *Defining SWRL rules and SQWRL queries.* The reasoning of SWRL rules can generate new facts based on the existing information, especially if it is not included in the exported BIM model. Several rules were defined in the proposed ontology based on the requirements defined in this research. The complexity of those rules varies, from rules that consider only one aspect to rules that consider several aspects and conditions to provide a multi-objective knowledge base. The SWRL provides class atom, individual property atom, and data valued property atom. A detailed discussion of each atom can be found in Ren, Ding and Li [4]. The symbol '^' is used to connect varied classes' and individuals' atoms. A question mark, '*?*', represents the variable in each atom. The symbol → can be used to connect antecedents. In cost estimation, to calculate the net area of a rectangular column (? ColAc), the gross area (?ColAg) needs to be subtracted from the area of steel bars (?CAs). The syntax *swrlb: subtract* was used to model this function. The data needed to calculate the appropriate area was extracted automatically from the IFC file based on the available dimensions for the appropriate section and the steel bars used. The data was added to the ontology as data type properties using the automatic data acquisition method. For instance, to calculate the gross area (?ColAg) of a rectangular column. The syntax *swrlb: multiply* is used to multiply width(?Cb) and length (?Ch). The gross cross-section area, the area of the reinforcement, and the net area of a rectangular column can be represented in SWRL rules as follows (Table 4).

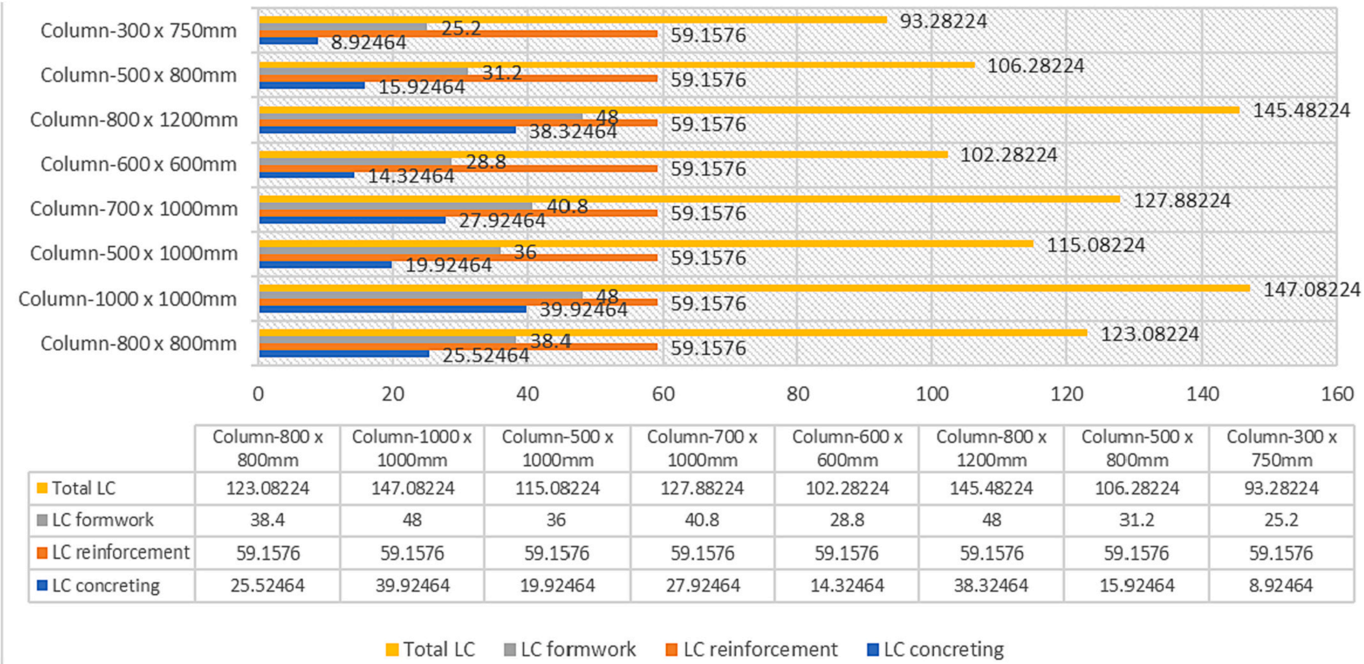



**Fig. 15.** The total labour cost with respect to the selected columns.

**Table 13**
Some of the SWRL rules used to answer Q-e.

| |
|---|
| *Rule4–1: Fire resistance time 60* |
| RectangleColumn(?Column) ^ hasName(?Column,?Name) ^ hasWidth(?Column,?Width) ^ hasCover(?Column,?Cover) ^ swrlb:greaterThanOrEqual(?Width, 200) ^ swrlb:lessThan(?Width, 300) ^ swrlb:greaterThanOrEqual(?Cover, 25) - > hasFireResistanceTime60(?Column, "R60") |
| *Rule4–2: Fire resistance time 90* |
| RectangleColumn(?Column) ^ hasName(?Column,?Name) ^ hasWidth(?Column,?Width) ^ hasCover(?Column,?Cover) ^ swrlb:greaterThanOrEqual(?Width, 300) ^ swrlb:lessThan(?Width, 350) ^ swrlb:greaterThanOrEqual(?Cover, 25) - > hasFireResistanceTime90(?Column, "R90") |
| *Rule4–3: Fire resistance time 120* |
| RectangleColumn(?Column) ^ hasName(?Column,?Name) ^ hasWidth(?Column,?Width) ^ hasCover(?Column,?Cover) ^ swrlb:greaterThanOrEqual(?Width, 350) ^ swrlb:greaterThanOrEqual(?Cover, 25) - > hasFireResistanceTime120(?Column, "R120") |

## 6. Framework testing and validation

The framework can be validated using scenario-based case testing to show whether it provides the necessary information through the proposed data exchange method. It should also allow end users to compare design choices related to sustainability and cost while considering design conditions based on the existing data in an IFC-based BIM model. An airport BIM model located in Nanjing, China, was used in this research. The BIM model was developed based on experts' input. The selected BIM model (Fig. 11) contains project and site information. It comprises two building stories including their properties. It consists of substructures such as concrete beams, concrete columns, and concrete slabs; superstructures such as concrete beams; and upper floor structures such as in situ columns, upper slab sections, and roof columns. The information related to sustainability and cost estimation was not included in the selected model. The proposed framework will provide the additional information automatically using the built-in SWRL rules because it is out of the sender's scope. This step will be part of the framework testing and validation process. The model was converted from RVT format in Revit to the IFC format using the embedded functionality in Revit software, and the IFC4 Design Transfer View (DTV) was selected to export the IFC file. The model showed a total of 664,280 entities, of which 3415 were building element entities, including beams (2962), columns (424), and slabs (29).

To assess the viability of the proposed framework, several objectives were defined.

(1) It was vital for the framework to enhance data exchange by delivering different data sets from a complex BIM model by focusing only on the critical information. The data exchange method was tested by applying it to the airport model to extract different data sets to check consistency and ensure no data was lost. Scenario-based case testing was used to validate this assumption.
(2) It was important for the proposed knowledge base to work with other systems and formats. This step focused on validating the knowledge base to ensure it was syntactically and semantically correct and no inconsistencies existed. This research proposed a

**Table 14**
Some of the SQWRL queries used to answer Q-e.

| |
|---|
| *Holistic design of rectangular column considering multiple aspects with C25 and R120* |
| C25(?Con) ^ hasfckC25(?Con,?Confck) ^ hasTotalCostC25(?Column,?TCost) ^ hasName(?Column,?Name) ^ hasTotalLabourCostColumn(?Column,?TotalLabCostColumn) ^ hasFireResistanceTime120(?Column, "R120") ^ RectangleColumn(?Column) ^ hasConcreteC25(?Column,?Con) ^ hasTotalEmbodiedCO2eC25(?Column,?TECO2) ^ hasWidth(?Column,?Width) ^ hasLength(?Column,?Length) ^ meetDesignConditionC25(?Column, "Yes") ^ hasCover(?Column,?Cover) ^ hasXC1(?Con,?expossure) - > sqwrl:select(?Column,?Name,?Width,?Length,?Cover, "R120",?expossure,?Confck,?TECO2,?TCost,?TotalLabCostColumn) |

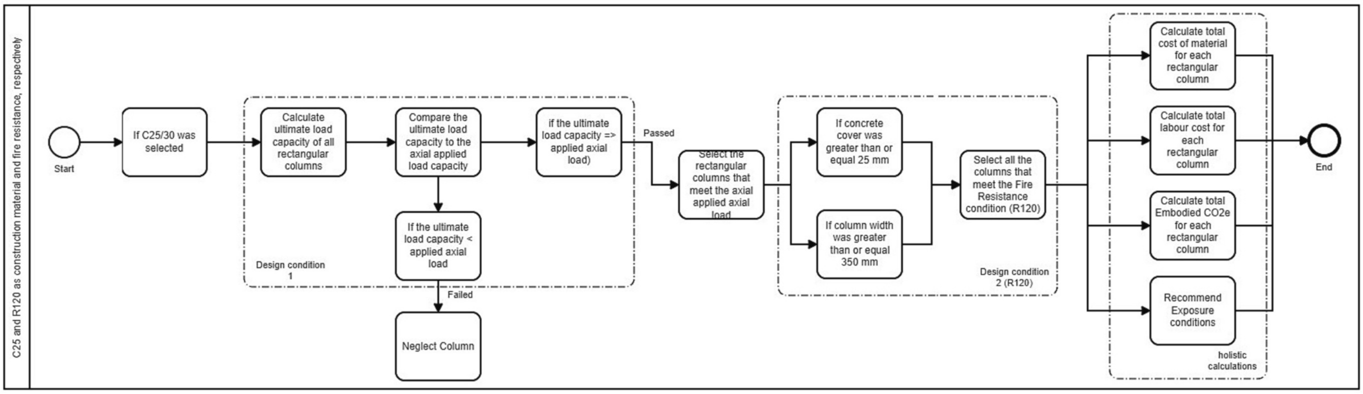



**Fig. 16.** Workflow of the developed multi-objective knowledge base considering C25/30 and R120 as construction material and fire resistance, respectively.

**Table 15**
Results collected from the Holistic design of rectangular column query with C25 and R120.

| Name | Cover (mm) | Fire Resistance | Exposure condition | Strength | Total Embodied CO2 (kgCO2) | Total material cost (USD$) | Total labour cost (USD$) |
|---|---|---|---|---|---|---|---|
| 1000 × 1000 mm | 25 | R120 | Suitable for exposure: (1) Carbonation-induced corrosion; (2) Freeze/Thaw Attack | 30 | 1073.97 | 387.269 | 147.0822 |
| 700 × 1000 mm | 25 | R120 | Suitable for exposure: (1) Carbonation-induced corrosion; (2) Freeze/Thaw Attack | 30 | 751.172 | 270.869 | 127.8822 |
| 800 × 1200 mm | 25 | R120 | Suitable for exposure: (1) Carbonation-induced corrosion; (2) Freeze/Thaw Attack | 30 | 1030.93 | 371.749 | 145.4822 |

data acquisition method to align the IFC file with the ontology. Ensuring that the terms and concepts were uniform and consistent throughout the ontology development was significant.

(3) It was vital to verify the framework's efficiency in providing a multi-objective knowledge base that considered single to multi-objective decisions and its ability to work with different sources of information. By using the existing data in the IFC-based airport model, the built-in SWRL rules were tested by processing several queries to show the reliability of the framework that considered various conditions and tested their ability to generate new facts.

### 6.1. Data exchange method

To validate the proposed data exchange method, a simple data extraction tool was developed to stress the technical feasibility of the proposed architecture. Python was used to develop a graphical user interface (GUI) using Tkinter, a standard GUI library for Python that creates fast GUI applications. The validation process was carried out by comparing the models before and after data processing to test the framework's ability to deliver data sets from a complex BIM model. The validation was performed by checking whether the necessary information was extracted correctly and without data loss. However, the tool supports the extraction of basic elements to elaborate on the process. Therefore, only elements such as beams, columns, and slabs were investigated.

The original model showed a total of 664,280 entities, of which 3415 were building element entities, including beams (2962), columns (424), and slabs (29) (Table 6). The engineer can upload the IFC-based BIM model. The users will have various options; they can extract information as required, including various data sets, or they can extract a group of building elements. After uploading the IFC file to the proposed prototype, several files were extracted, such as the Slabs-IFC file, Beams-IFC file, Columns-IFC file, SCDS for structure design, SCDS for cost estimation, and MCDS using the defined data sets. The exported files were imported into the IFC analyser for analysis. It was shown that the number of entities was reduced in the newly generated files while the number of building elements was maintained. The number of elements extracted showed the accuracy of the data processing, and no data loss was noted. The developed data exchange method is significant in simplifying the process of obtaining related data from a BIM model where users can use subsets or specific elements for their design analysis instead of working with a complex model. Consequently, it provides a flexible input that can merge easily with other technologies and data.

### 6.2. Reasoning through Protégé plugins

The ontology reasoner Pellet was used to check that the developed ontology was syntactically correct. This was carried out in two stages: (1) before applying the data acquisition method and (2) after aligning the IFC data with the proposed ontology. Based on the reasoner, the knowledge base structure was syntactically correct, and both stages recorded no inconsistency. Using existing resources and ontology structures validated the proposed ontology semantically because using the structure and terms in the previously validated ontology, such as IfcOwl, maintained consistency in the proposed ontology, which is not the case with ontologies that were developed from scratch. The latter ontologies required further consultations from domain experts to provide their validity. After the ontology was semantically and syntactically validated before and after the ontology alignment process, it was further validated through a case-based scenario (Section 6.3) to confirm whether the ontology met the requirements and to test its capability to produce multi-objective decisions.

### 6.3. Holistic decision-making knowledge base validation

This part of the framework validation focused on the holistic knowledge base development and its ability to work with different sources of information to generate multi-objective decisions. Due to limited time and resources, it was difficult to explore all types of building structures. Columns are one of the most critical components in building design and are crucial to structural stability. The height of the concrete columns considered is equal to 4 m. Normally, the column dimensions are assumed to provide the required results in an ontology. However, the proposed data acquisition method eliminates the manual input and provides the actual dimensions from an IFC-based BIM model, reducing assumptions.

The data exchange method developed in this research was used to improve efficiency in reasoning and querying because this procedure can reduce the processing time by only showing critical information instead of the entire model. Following the data sets extracted in the previous section (Section 6.1), the MCDS was used as input for the automatic data acquisition method because only the minimum required data will be used. Several questions were stated to test and validate the developed knowledge base.

Q-a: By using the MCDS proposed, are the existing rectangular columns structurally feasible considering the load capacity?
Q-b: By using the MCDS proposed, what is the total embodied carbon content in each rectangular column used in that IFC file for different concrete materials while considering the load capacity criteria?
Q-c: By using the MCDS proposed, what is the cost of material used for each rectangular column?
Q-d: By using the MCDS proposed, what is the cost of the total labour for each rectangular column by considering the cost of concreting, reinforcement, and formwork?
Q-e: Can the proposed framework review the IFC-based BIM model in parallel with all the factors mentioned while considering design conditions such as load capacity and fire resistance requirements to make decisions in the early design stage?

To answer those questions, several SWRL rules and SQWRL queries were constructed. After running the reasoning process, several types of columns were used in this project, such as Column-800 × 800 mm, Column-1000 × 1000 mm, Column-700 × 1000 mm, Column-600 × 600 mm, Column-800 × 1200 mm, Column-500 × 800 mm, Column-500 × 1000 mm, and Column-300 × 750 mm. After screening the results, only one element of each type of column was determined to demonstrate the results.

#### 6.3.1. Checking building elements against axial load capacity

The ultimate axial load capacity of a concrete column depends on the strength of the concrete used and the strength of the reinforcement. Therefore, the ultimate axial load capacity of the extracted columns was calculated based on the types of concrete. The yield strength of the reinforced bar was set to 415 N/mm2, and six reinforcing bars with a diameter of 20 mm were used. Using C25 as an example, the ultimate load capacity of a rectangular column with C25 can be represented in the SWRL rule and SQWRL query as follows (Table 7).

Fig. 12 shows the ultimate axial load capacity for different sections of rectangular columns with various types of concrete. This ultimate axial load that was calculated using the SWRL rules was compared automatically to the applied axial load to check whether the existing columns met the design criteria. In this research, the axial load applied to the rectangular column is assumed to be equal to 12000KN. It was shown that when C25 and C35 were used, the ultimate load capacity of some columns, such as Column-600 × 600 mm, Column-500 × 800 mm, and Column-300 × 750 mm, did not have enough strength to support the transferred loads. If those types of concrete are selected, some sections would require higher concrete strength or a change in the section dimensions to resist the applied load. On the other hand, it was shown that as the strength of the concrete increases, the chance of reducing the section dimensions becomes feasible. The proposed rules provided a single objective decision.

This applied axial load limit has been modelled using the syntax *swrlb:greaterThanOrEqual*(?CNed, 12,000,000) and has been stored in a variable called meetDesignCondition. This variable will be used to model other SWRL rules to ensure that the design condition (axial load capacity) is met while reviewing other aspects to move from single to multi-objective decision-making. Using C25 as an example, this condition can be represented in the SQWRL rule as follows (Table 8).

#### 6.3.2. Assessing building elements against sustainability aspects while considering axial load capacity

In this research, the embodied carbon content is the indicator of the extracted columns' environmental impact. As mentioned, it is necessary to consider the factors simultaneously to determine a holistic decision. The embodied carbon content and the remaining aspects were reviewed while evaluating only the columns that satisfied the applied load capacity. The variable meetDesignCondition was used to apply the design condition factor. An example of the rules and queries is modelled in the proposed ontology (Table 9).

In Fig. 13, the total embodied CO2 for each column type was calculated using concrete types such as C25, C35, C80, and C90 while considering design criteria. Users can investigate the effects of concrete materials on the selected building elements. Not all the columns passed the design condition (the applied axial load limit). For instance, when C25 was selected, only three columns passed the check: Column-1000 × 1000 mm, Column-700 × 1000 mm, and Column-800 × 1200 mm. The proposed ontology calculated the embodied $CO_2$ only for those columns. In Fig. 13, the column with the lowest total embodied $CO_2$ was Column-300 × 750 mm, using concrete C80, while the column with the highest total embodied $CO_2$ was Column-1000 × 1000 mm, using concrete C90. Using Column-300 × 750 mm as an example, using this type of column with C80 instead of C90 can decrease the total embodied $CO_2$ by 11.6%. Furthermore, the column with a minimum embodied carbon content is normally considered the most sustainable design solution. However, another design consideration is required, mainly related to design safety.

The cost of the material used in a column was calculated in relation to the economic aspect of sustainability using the following rule and query (Table 10).

The cost of material can be calculated according to the different types of elements and concrete used. For instance, a column with dimensions of 300 × 750 mm and a depth of 4 m using concrete C90 costs $232 (Fig. 14). Using Column-300 × 750 mm with C80 instead of C90 decreased the cost of the material used by 7.4%. The column with the lowest total cost was Column-300 × 750 mm with concrete C80, while the column with the highest total cost was Column-1000 × 1000 mm with concrete C90. Although using high-strength concrete can reduce the section dimension of a column, it cannot be applied to all scenarios. In some cases, reducing a column's section dimension is impossible due to factors such as fire resistance, among others.

#### 6.3.3. Considering the cost of the labour based on dimensions and reinforcement used

To evaluate the total labour cost of a rectangular column early in the design stage, several SWRL rules and SQWRL queries were implemented in the proposed ontology. To calculate the labour cost of column concreting, reinforcement, and shuttering work, the following SWRL rules were added in Table 11.

The summation of all three variables results in the total labour cost for the column, which was represented in the ontology in Table 12.

The syntax *swrlb:add*(?TotalLCC,?LCC,?LCR,?LCF) was used to model the total cost variable. The output of executing the cost query is presented in Fig. 15, where the total labour cost of rectangular columns is calculated based on the labour cost of column concreting, reinforcement, and shuttering work.

### 6.3.4. Multi-objective knowledge base considering various aspects

The previous sections discussed the possibility of combining different resources to produce collective decisions. These aspects were combined with several restrictions related to design criteria. For instance, taking C25/30 as an example, an engineer can look into several factors, such as embodied carbon content, exposure condition, costs of material and total labour, while considering design conditions such as fire resistance, which is an additional condition that should be considered in column design. Information on this factor is usually collected from tables or statements, as mentioned in Section 2. Three different conditions of fire resistance have been modelled. They rely on two factors: the minimum width of the selected column and the minimum concrete cover (the distance between the surface of the concrete and the reinforcement). The cover was set to 25 cm in this study, and the dimensions were extracted automatically from the IFC. In the proposed ontology, this has been modelled as follows (Table 13).

These conditions were implemented using the syntaxes *swrlb:greaterThanOrEqual* and *swrlb:lessThan*. The increase in column dimensions and the concrete cover could result in fire resistance. However, selecting the column dimension also affected the ultimate load capacity and sustainability. Those conditions need to be considered in structural design. Those factors were put into one SQWRL query to provide a multi-objective decision (Table 14). Furthermore, exposure conditions were added according to the strength of the concrete. Because various concrete strengths were set as a constraint, these conditions will be recommended when reviewing a certain type of concrete. For instance, when selecting C25/30 concrete, the query will show that this concrete is suitable for exposures such as carbonation-induced corrosion and freeze/thaw attack.14

The workflow of the developed multi-objective knowledge base considering C25/30 and R120 as construction material and fire resistance, respectively, is shown in Fig. 16.

Step 1: If C25/30 was selected as concrete material ➔ Calculate the ultimate load capacity of all rectangular columns ➔ Compare the ultimate load capacity to the axial load capacity (applied axial load) ➔If the ultimate load capacity is less than the applied axial load ➔ Failed – Neglect column.

Step 2: If C25/30 was used as the concrete material ➔ Calculate the ultimate load capacity of all rectangular columns ➔ Compare the ultimate load capacity to the axial load capacity (applied axial load) ➔ If the ultimate load capacity is greater than or equal to the applied axial load ➔ Pass – Select the rectangular columns that meet the axial applied axial load.

Step 3: If the concrete cover of the selected rectangular columns that met the axial applied axial load was greater than or equal to 25 mm AND If the column width was greater than or equal to 350 mm ➔ Select all the columns that meet the Fire Resistance condition (R120) ➔ show and calculate the following parameters:

(1) Recommend exposure conditions
(2) Calculate the total cost of material for each rectangular column
(3) Calculate the total labour cost for each rectangular column
(4) Calculate the total embodied $CO_{2e}$ for each rectangular column

The outputs of the holistic design of the rectangular column considering multiple aspects with C25 and R120 are presented in Table 15.

## 7. Discussion and conclusion

This paper presents a framework that combines data exchange and semantic web technology to eliminate inefficiencies in data sharing and improve decision-making in the early design stage. One main contribution of this research is to align the developed multi-objective knowledge base with the data exchange method to extract information from an IFC file and merge them with the data presented in the developed ontology to eliminate human involvement by decreasing manual input. Thus, the proposed approach is unique compared to previous research. Most previous ontologies require human intervention to add data, which can be time-consuming and require users to know how to add the instances and values. Hence, the ontology was built around two sources of data: (1) static data, where the information is collected from manuals, papers, databases, and standards, and (2) dynamic data, which represents the information collected from an IFC. It was shown that the proposed data acquisition method assisted in producing a more dynamic knowledge base that connects dynamic data to static data. Consequently, this approach has proved to be more efficient than a manual approach by adding data to the knowledge base. The proposed ontology was supported by SWRL rules to generate new facts, especially if that information is not included in the BIM model. The SWRL rules helped automate all the manual calculations and generate new facts based on the data in an IFC file. The built-in rules allow the end-user to review and compare different design alternatives by considering various factors related to sustainability and cost at an early stage. The complexity of those rules varies from rules that consider only one or several aspects to provide a multi-objective decision. Future work can include assigning a weight coefficient for each aspect, which can help rank those aspects from major impact to minimum impact. Consequently, it can help users observe which factor needs to be considered before the other, which can enhance the decision made within a project.

However, this study has several limitations. In practice, the creation of the BIM model affects the use of the automatic data exchange method, which may vary according to the modelling method. Due to the limited time and resources for this research, it is difficult to explore all types of building structures. Consequently, the reasoning and query functions in the proposed ontology focused mainly on rectangular columns, and a thorough knowledge base covering various building elements will be developed in the future. The created ontology's built-in mathematical functions are limited to performing fundamental operations. The computation techniques provided by SWRL restrict the combination of many distinct parameter values. Advanced computational techniques will be required to cover more complex equations. Moreover, the ontology system created in this study needs the “user” to manually enter data, such as the story height in the selected scenario. Consequently, it is anticipated that a greater degree of automation will be required to eliminate the need to add the data manually. The reasoning and query functions in the proposed ontology, including the embedded SWRL rules, rely mainly on the available resources and standards and cover the most necessary building elements.

The AEC sector is currently in a transitional phase towards a more progressive approach towards digital application. This transition will provide a more advantageous platform for effectively structuring the large amount of information produced throughout an asset's delivery and operation, unlocking the potential to gain a greater understanding towards knowledge-based decision-making. With an overall global push towards the standardisation of information management within AEC projects, the ability to structure information to be machine-readable could provide a base for interdisciplinary knowledge to be collated so that information can be queried across all disciplinary perspectives. Utilising only the necessary information from a BIM model and combining it with semantic web technology has the potential to provide a rich semantic environment that can solve some of the interoperability issues. However, implementing such a framework requires much investment in refining the datasets and linking all the relevant data, which also requires knowledge from domain experts. With the development of the data exchange framework and multi-objective knowledge base presented in this study, the focus on the efficiency enhancement of graph databases becomes increasingly vital. Future research will emphasize optimizing the structure of graph databases to better integrate and interact with original engineering data, as well as align with existing ontologies. This could further reduce the possibility of human involvement and errors while providing more efficient and precise tools for data analysis and decision-making support. By leveraging more advanced graph database technology, it can achieve more complex querying and reasoning functions, thereby driving decision-making in the early design stage towards more sustainable and cost-effective directions.

## 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

Data will be made available on request.

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