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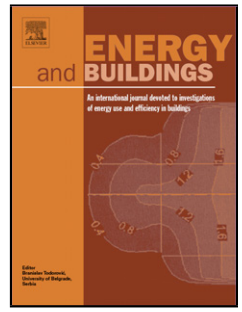

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Highlights

- An ontology based decision support system is developed for structural design.
- System provides multiple optimised solutions with low embodied energy and carbon.
- System provides selection of structural material suppliers.
- OWL ontology is used to integrate multiple domain knowledge in a knowledge model.
- SWRL rules is applied to infer new facts and query ontology.

Ontology-based approach for structural design considering low embodied energy and carbon

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Abstract

Buildings account a large share of energy consumption and greenhouse gas emission. Numerous methods have been applied to operate buildings more efficiently. However, the embodied energy and carbon are identified increasingly important in terms of sustainability throughout building life cycle. In traditional building structural design approach, the engineers pay little attention on environmental aspect which has been recognised as one of the most important factors to consider in modern integrated building design approach. The emergence of Semantic Web technologies provides more opportunities to assist structural engineers in improving building sustainability. The study presented in this paper investigates how ontology and Semantic Web rules can be used in a knowledge-based system, to represent information about structural design and sustainability, and to facilitate decision-making in design process by recommending appropriate solutions for different situations. A prototypical system named OntoSCS (Sustainable Concrete Structure Ontology), including a Web Ontology Language (OWL) ontology as knowledge base and SWRL rules providing reasoning mechanism, is developed to offer optimised structural design solutions and selections of material suppliers. Embodied energy and CO_2e are used in the system as indicators to evaluate sustainability of structure. Both ontology reasoner and case studies are employed for system validation.

Keyword

Sustainable structural design; Ontology; SWRL; Embodied energy and carbon; Decision support system

1. Introduction

The building construction sector has been identified as one of the largest shares of natural resource and energy consumption. According to the estimates from Edwards [1] and Smith et al. [2], in the United Kingdom, buildings account approximate 50% of the total commercial energy consumption of the country, and release around 300 million tonnes of CO_2 each year, which take up to around 50% of total CO_2 emission of the country.

There are a number of ways of consuming energy by modern buildings [3]. As most energy is consumed in operation stage to run and maintain the building, a large number of researchers focus on reducing the operational energy and carbon dioxide (CO_2) emission to improve sustainability of buildings. Emerged technologies such as renewable energy and artificial intelligent energy management have drawn many attentions and have been widely investigated and implemented. However, prior to operation phase, energy used in building raw material extraction, material processing, components manufacturing and transportation also accounts considerable share of energy consumption throughout building life cycle and causes significant environmental impact. To quantify the usage of energy in this phase, embodied energy is introduced to measure the quantity of energy that is required to process material and supply to the construction site [4]. Likewise, the embodied carbon is introduced to describe the emission of energy-related greenhouse gas (GHG) especially CO_2 during this phase. Although the focus of building regulations in the UK has been on operational energy and carbon emission, the importance of embodied energy and carbon is being recognised more rapidly. Because zero carbon buildings are promoted in UK for residential in 2016 and for other buildings in 2019, then the vast majority of whole life cycle energy consumption and carbon emission are embodied in the building materials [5]. In aggregate terms, embodied energy consumption is responsible for significant percentage of total energy use of a country. In the UK, this part is estimated to account for 10% of national energy consumption [6]. In terms of single building, a study by Sartori et al. [7] found a large variation of the percentage of embodied energy's share in total energy consumption, from 5% up to 40%.

Because embodied energy and carbon correspond to energy usage and CO_2 emission during the production of building materials and components, unlike the operational energy and CO_2, the impact of embodied energy and carbon is unchangeable to environment once the building completed. From structural engineers' perspective, there are mainly three ways of reducing embodied energy and carbon [8]. Firstly, selection of building materials and structural components in early design stage is crucial. Building materials with less embodied energy and carbon become a priority of material selection, such as cement combined with cementitious additions and recycled aggregates. Secondly, improving supply chain of construction materials and selecting nearby suppliers would decrease the embodied energy and carbon generated by transport. Last but not least, optimisation of structural members' dimensions using materials with different strength classes could also offer savings of embodied energy and carbon. To consider these ways as a whole and help structural engineers to understand the impact their design solution might have in terms of the sustainability of building, a holistic design approach of modelling multiple domain knowledge is greatly demanded.

In recent years, there are significant achievements of computer science and artificial intelligence in both theoretical and practical aspects. In the meanwhile, findings from research suggest that modelling of disparate knowledge on different domains requires a rich semantics language that can be read by not only human but machines [9-11]. Ontology as one of the emerging Semantic Web technologies has been applied for knowledge management, including modelling, developing, sharing and utilising knowledge in a wide range of domains, such as agriculture [12], bioinformatics [13], economy [14], medicine [15, 16] and recently building construction [17-19]. The core features of ontology, inclusive of semantic structure, machine processing capability and reasoning function, provide an important opportunity to facilitate the development of computer aided decision support system.

The main objective of the study is to use ontology as a knowledge base managing multiple domain knowledge (building sustainability and structural design), in order to assist structural engineers in reducing environmental impact at conceptual design stage. A ontology-based decision support system named OntoSCS (sustainable concrete structure ontology) is developed to provide multiple optimised design solutions not only for structural feasibility and cost, but also minimum embodied energy and carbon. Although the building structural forms are varied and each building is a combination of many materials, it is difficult to explore all of them due to the limit of research resource and time. Thus, reinforced concrete structure and its constituents are taken as the initial attempt and focusing point in this study. The reason of choosing concrete is firstly because of the heavy use in the vast majority of construction projects over the world. Secondly considering the whole life sustainable performance of a building, concrete is a very useful material in reducing the operational CO_2 and energy loads thanks to its thermal mass and night time cooling features. However, it is worthwhile to note that the methodology and procedure presented in this paper can be nonetheless applicable to other building materials or forms.

The remainder of this paper is organised as follows. Section 2 begins with introducing the background of embodied energy and carbon, and looks at existing work in the field of sustainable concrete structural design. Section 3 gives a brief overview of the Semantic Web technology and ontology, then reviews applications of Semantic Web. Section 4 is concerned with design methodology and development process of OntoSCS ontology. A case study including three specific applications for system validation is demonstrated and analysed in Section 5. Finally, Section 6 concludes the key findings of this study, and identifies future research.

2. Review of sustainable structural design

2.1 Embodied energy and carbon

As embodied energy and CO_2 are taken as indicators to measure sustainability of building structures, an overview about their concepts including respective assessment methods is given in this section. To measure the quantity of embodied energy of construction materials, different practical approaches with different study boundaries are adopted. They are commonly known as cradle-to-gate, cradle-to-site, and cradle-to-grave [20]. It should be noticed that these approaches are equally valid to be used to consider the embodied carbon, although the definitions of them below are specifically for embodied energy.

- A cradle-to-gate approach defines the embodied energy as the energy required to extract raw materials and process them.
- A cradle-to-site approach is an assessment covering partial building component life cycle from raw material extraction to transport them to construction site.
- A cradle-to-grave approach is a whole life cycle assessment including not only initial embodied energy as introduced in other two approaches above, but also recurring embodied energy and demolition energy.

Numerous databases and tools have been developed by institutes and companies to measure the values of embodied energy and carbon associated with different building materials and establish inventories [5, 21, 22]. Most values adopted in this study are taken from the ICE (Inventory of Carbon & Energy) database [21] which is developed by Hammond and Jones [4] from University of Bath. This inventory is a reliable and open-access database providing over four hundred values of embodied energy and carbon associated with construction materials, and is regularly updated and extended with new data from technical and scientific literature. It offers practical references for both academic researchers and industry professionals to allow them to analyse and calculate the amounts of embodied energy and carbon in products, systems and whole buildings. Therefore, it has been employed by various developers of carbon and environmental footprint calculators, for instance the Environment Agency's carbon calculator for construction. Moreover, in addition to the adoption of cradle-to-gate approach, the ICE also provides a sub-model incorporated in the database, which enables users to estimate the values of embodied energy and carbon for cements, mortars and concretes according to their constituent materials used in real projects. For example, in the case of cement, its embodied energy per kilogram (E) could be modelled using:

$$E = (1 + M)(Cxc + Sxs + Axa + Wxw + Rxr + Pxp + O) + T \qquad \text{(Equation 1)}$$

where M is the wastage factor (%), C, S, A, W, R and P are masses (in kg) of cement, sand, aggregate, water, cement replacements and plasticisers respectively, O is the operational energy and T is the transport energy of the final product. The parameters xC, xS, xA, xW, xR and xP are the embodied energy coefficients (MJ/kg) for the six materials listed above. The values of embodied energy and carbon used in this study are from ICE database version 2.0, which embodied carbon data has been converted to CO_2e which captures more than just carbon dioxide.

2.2 Sustainable structural design

In recent years, there has been an increasing amount of literature on studying the reduction of embodied energy and carbon in building structures, which covers a wide area of research from the selection of structural frame form and individual tall building height, to the optimisation of structural components size and structural materials alternatives [23-25].

A study undertaken by Arup and The Concrete Centre [23] investigated the embodied CO_2 in several typical structural frames for non-residential buildings including commercial, hospital and school buildings. Different structural solutions including concrete flat slab, in-situ with precast concrete, PT (Post-Tensioned) flat slab, composite frame, steel with precast concrete, slimdek are considered for all three building types, in addition two long span solutions that PT (Post-Tensioned) band beam and long span composite are studied for commercial office only. The study used the cradle-to-gate embodied CO_2 values from Bath ICE database as well to measure the variations of total embodied carbon in building structures. By analysing the results of base case study and specification study, optimising the embodied CO_2 of the structure would not adversely affect the whole building impact. In general, the concrete building performs better than steel building and there is great potential to minimise the embodied carbon by careful design and specification of concrete components in buildings. The choice of concrete specification shows more significant impact than the choice of frame material in terms of embodied CO_2 reduction.

Foraboschi et al. [24] discussed the cradle-to-gate embodied energy of high building structures in the newly published paper. A reinforced concrete central core and rigid frame was taken as reference structure which was design for 20 to 70 stories buildings. Six types of floor systems were taken into consideration including steel–concrete floor, RC (Reinforced Concrete) slab, lightweight floor system 1 polypropylene blocks, lightweight floor system 2 low-density polystyrene blocks, lightweight floor system 3 high-density polyethylene spheres, and lightweight floor system 4 polypropylene element removed. The total corresponding embodied energy of each case was calculated and compared to others. The result indicates that a sustainable tall building structure with lowest embodied energy is not necessarily the one with lowest weight. Additionally, steel structure consumes more embodied energy than reinforced concrete building. More importantly the embodied energy is proved to be a viable tool for sustainable building design.

To determine the effect of structural component dimension on building embodied energy, Yeo et al. [25] employed numerical optimisation techniques to minimise the embodied energy in their work. Rectangular beam as a simple example of reinforced concrete structural member with fixed moment and shear strength was analysed to obtain the minimum embodied energy. A domain of feasible beam design solutions demonstrates the trend that total embodied energy varies according to the different dimensions. Given the values of the embodied energy in this study, the result shows a reduction of 10% in total embodied energy with slight cost increase. Clearly, this paper illustrates the benefit of structural member optimisation for embodied energy savings in reinforced concrete structure.

Overall, the studies mentioned so far suggest that structural design solutions have significant impact on embodied energy and carbon in buildings. Moreover, there is a great potential of reducing embodied energy and carbon through selecting optimised structural design alternatives and material specifications. However, from a practical point of view, a knowledge-based decision support system may add more capability and flexibility to the methods mentioned above. It helps the structural engineers to understand and organise the relationships between structural design and building sustainability, taking the embodied energy and carbon into account at design stage to minimise the whole life cycle energy consumption and carbon emissions. In next section, the Semantic Web technology and how it can be applied to building design area are explored.

3. Overview of the Semantic Web technology

3.1 The Semantic Web

World Wide Web (WWW) has become the largest distributed information repository in human history. One of the main advantages of WWW is using Hypertext Markup Language (HTML) syntax-based information representation that makes information accessing and dissemination more easily by key-word search and link navigation. However, with the explosion of contents and data on the web, the weakness of current web has been exposed. Retrieval right pieces of information and utility of knowledge are increasingly difficult with traditional way which relies on search engine to browse the web filling with extremely abundant information. However, efficient information exchange is not the only inspiration of emergence of the Semantic Web. Hitzler et al. [26] explains two more motivations that provide conceptual foundations of the Semantic Web. One is building models that can describe the complex reality of the word in abstract terms. The second is computing with knowledge, which allows computers to automatically draw meaningful conclusions from knowledge model.

In order to meet these demands, the Semantic Web has emerged for a web of data. The WWW Consortium describes the goal of Semantic Web is giving information explicit meanings that are related to the real world objects, making it easier to understand and process by machine as well as human, and integrating information from diverse sources available on the Web. In reality, it is hardly possible to realise Semantic Web to all human knowledge on the web. From a practical point of view, enabling machine to access more information is a more reasonable purpose of developing Semantic Web. More importantly, not only directly related to web, Semantic Web technologies also can be applied widely in other areas. The vision of Semantic Web concludes major advantages [27] which many research works could benefit from, such as data annotation [28], decision support [9, 29-31], data interoperability [32], information retrieval and natural language processing[28]. Therefore, our study aims to explore how we can take advantage of the Semantic Web development by implementing Semantic Web components in decision support and recommendation system for sustainable building domain. As one of the key component of Semantic Web, ontology is crucial to the implementation, which is introduced in the following part.

3.2 Ontology

Ontology plays a key role in Semantic Web development since it provides a framework to structurally model knowledge of a given domain in a format that can be processed by machine and human. The origin of the term ontology is philosophy, which means the study of the nature of existence. However in computer science, the meaning of this term has been changed. A most referred definition of ontology is 'a formal, explicit specification of a shared conceptualization'[33]. Typically an ontology consists of a group of concepts and the relationships between concepts including hierarchies of classes, properties, data values and restrictions of properties.

Modelling complex knowledge requires formal logic based expressive representation languages to conduct logic reasoning on knowledge [26]. OWL is one of the languages that are able to meet this requirement. OWL stands for Web Ontology Language that has been recommended by W3C as a standard for ontology modelling since 2004. It is designed to reach a balance of rich expressivity and efficient reasoning. Furthermore, to extend the flexibility of OWL, three sublanguages of OWL with different degrees of expressivity are developed for users to select.

- OWL Full - OWL Full is the most expressive language of the three, containing all of RDFS. However, it is undecidable due to lack of restrictions and semantically difficult to understand and work with [26]. Therefore, it is hardly supported by any reasoning tool.
- OWL DL (Description Logics) - OWL DL is contained in OWL Full, with decidability and also expressiveness. Because of its root of description logics, it is the most widely studied and used ontology language. Hence it is supported by most reasoning software tools.
- OWL Lite - OWL Lite is contained in both OWL Full and OWL DL. It has less expressiveness that the others yet it is highly decidable.

There is an increasing trend of adoption of OWL in many applications of various domains. Considering the limitation of OWL Lite in capturing class hierarchies and lack of reasoning tools for OWL Full, like most studies, we adopt OWL DL as the ontology language in this study.

3.3 SWRL

One of the limitations of OWL is that only structural inference such as subsumption and identity is provided [34]. In reality, more advanced and flexible inference such as deductive reasoning capability is required beyond the structural inference. Therefore, a Semantic Web rule language on top of ontology is needed for more extensive purposes. Golbreich [35] concludes five main situations that rule can be applied: “standard-rules”, for chaining ontologies properties, such as the transfer of properties from parts to wholes, “bridging-rules” for reasoning across domain, “mapping rules” for data integration between Web ontologies, “querying-rules” for expressing complex queries upon the Web, “meta-rules” for facilitating ontology engineering (acquisition, validation, maintenance). For this reason, SWRL (Semantic Web Rule Language) is proposed to extend OWL DL with first-order rules and provide semantic and inferential interoperability between ontology and rule. The SWRL overcomes the limitation of OWL by using the existing facts such as classes and properties from OWL ontology knowledge base to infer new facts. In order to perform application specific reasoning, the ontology in this study is enhanced with SWRL rules.

SWRL includes a high-level abstract syntax for Horn-like rules [36] which have the form of an implication between an antecedent and a consequent. Both consist of conjunctions of atoms that are represented symbolically as:

$$A_1, \dots A_{n-1}, A_n \rightarrow B$$

where A_i and B are atomic formulas, where i=1,2,3,…,n.

Each of the atoms could be class, object property, data property, instance or built-in from OWL ontology. The variables used in atoms are indicated using a question mark prefix; for example, A(?x), B(?x, ?y), sameAs(?x, ?y), hasvalue(?x, 1).

3.4 Applications

In recent years, a large and growing body of literature has investigated the implementation of Semantic Web technologies, especially the application of ontology. Considerable amounts of research have developed a broad range of ontology applications across medicine [16], biology [37], transportation [38], agriculture [12] and economy [14]. Ontology as an emerging Semantic Web technology surely has drawn researchers’ attentions from building construction industry due to the increasing demand of information and knowledge management. Significant progress has been made theoretically and practically in building construction sector. Efforts to establish frameworks of structurally representing and reusing building related knowledge have been undertaken [39] [40] [41]. Particularly in building information modelling domain, many ontologies are developed to facilitate the information sharing and exchange with a collaborative environment. For example, the Industry Foundation Classes (IFC) by BuildingSMART has been progressively developed to provide a widely used platform where construction data could be exchanged seamlessly [42]. Another example is the e-COGNOS project [43], which proposed a prototype ontology for the construction domain to support semantic knowledge management including semantic indexing, information retrieval and ontology-based collaboration. In 2013, Abanda et al. [27] conducted a comprehensive review of over 120 refereed articles on built environment Semantic Web applications, which reflects a trend of shifting from traditional construction applications to Semantic Web based knowledge and information intensive applications.

Moreover, ontology and Semantic Web technologies have been increasingly applied to develop knowledge-based systems to support complicated decision-making processes. Abanda et al. [9] developed PV-TONS ontology to facilitate system decision-making in recommending appropriate choices of photovoltaic system. Wang et al. [44] proposed a rule-based ontology reasoning method to support decision-making for manufacturers in China steel industry. Saa et al. [45] presented an ontology-driven decision support system for designing complex railway portal frames by developing a knowledge-rule database. Haghighi et al. [15] published a paper describing how to improve medical emergency decision-making by applying ontology in intelligent decision support system.

Having reviewed the key concepts of Semantic Web and its applications, in the following section we discuss how the structural design and sustainability domain knowledge can be represented using ontology to assist decision-making in design process.

4. Design and development of OntoSCS

In this section, the system framework of OntoSCS will be firstly introduced and followed by specifying the details of how the system is developed.

4.1 System framework and key components

The OntoSCS system consists of three core parts as shown in Fig. 1: knowledge base, ontology management system and rules engine. The knowledge base is the most important part in this system as ontology model and SWRL rules are stored in the form of OWL file. The ontology management system provides editors for both ontology and rules to create and update ontology. In this case Protégé 3.5 software code is employed as this role. Rules engine, for instance Jess engine, reads the existing facts in ontology and rules defined by the knowledge engineer to deduct new facts to ontology. The communications between ontology and rules engine are achieved by the bridge plug-in of ontology management system, for example SWRL Jess Bridge in this study. End users such as structural engineers, interact with OntoSCS system by inputting design requirements in the form of SQWRL queries through the query interface of Protégé, and acquiring feasible design solutions from the output tab. In addition, to check the consistency of ontology, reasoner Pellet 1.5.2 is deployed in this system as the reasoning engine. A flowchart of the system framework including some key components is specified below.

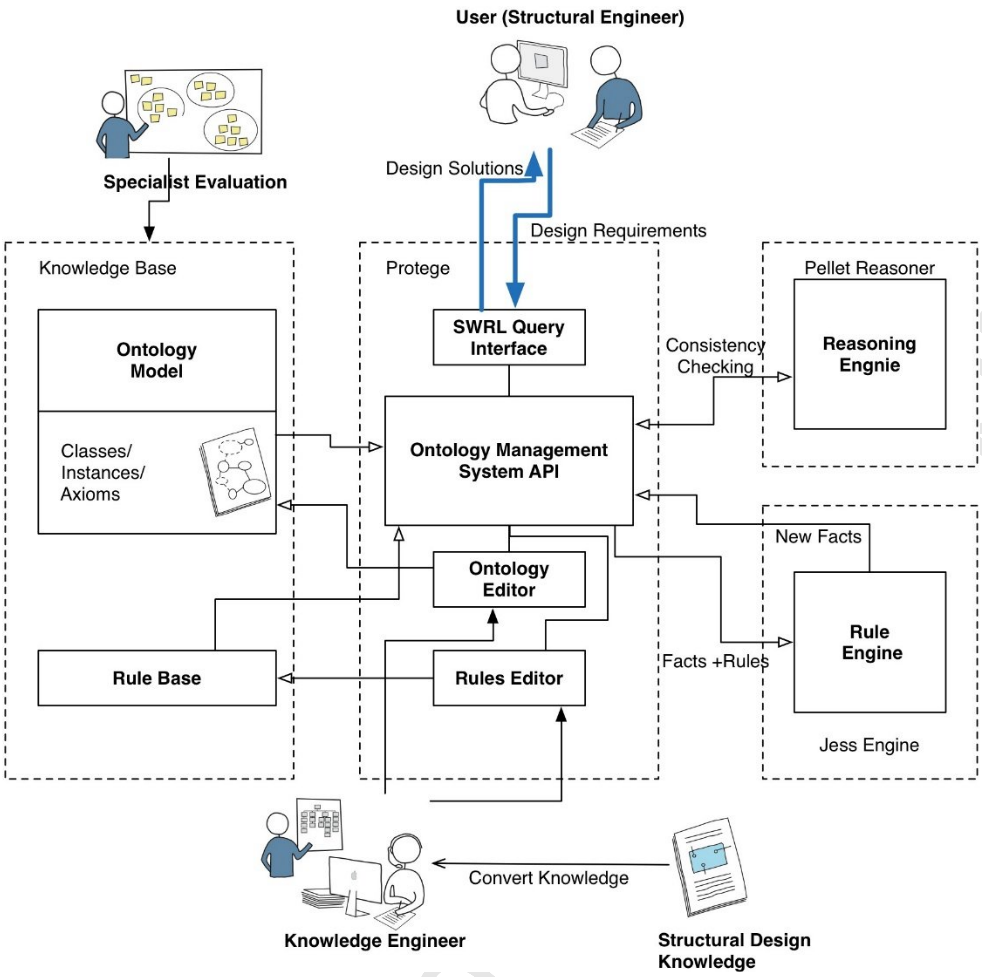

Fig. 1. OntoSCS system framework.

- Ontology editor

  Protégé-OWL 3.5 is an open-source tool that enables end users to create and update ontologies. One advantage of Protégé is that it is compatible with most OWL syntax validators. Comparing with other ontology editors, there are more abundant resources of learning and implementing Protégé. Moreover, many plug-ins of Protégé for various applications have been developed.

- Rules engine

  Jess is a tool for building rule based knowledge systems which is a set of rules that can be repeatedly applied to a collection of facts about the world and executed to generate new facts. Jess uses a special algorithm called Rete to match the rules to the facts. Rete makes Jess much faster than a simple set of cascading if-then statements in a loop.

- Ontology reasoner

  Pellet 1.5.2: Pellet is an OWL 2 reasoner which provides standard and cutting-edge reasoning services for OWL ontologies.

- Plug-ins

  SWRLTab: This is a Protégé-OWL 3.5 plug-in that facilitates the writing of SWRL rules.

  SWRL Editor: The editor supports editing and saving of SWRL rules in an OWL ontology.

SWRL Jess Bridge: A bridge for the Jess rule engine is provided in the Protégé-OWL distribution.

SQWRLQueryTab is a plug-in to the Protégé-OWL SWRLTab that provides a graphical interface to work with SQWRL queries.

SWRLJessTab is a plug-in to the SWRLTab that supports the execution of SWRL rules using the Jess rule engine. It provides a graphical interface to interact with the SWRLJessBridge.

4.2 The development of sustainable concrete structure ontology

The ontology is developed in two environments—ontology editor (to contain the knowledge model) and reasoning environment (to facilitate rule-based reasoning). The developments in the two environments are explained as following.

4.2.1 Ontology development

Developing ontology is a process of knowledge engineering. To date various methods have been applied to develop knowledge-based systems [46]. CommonKADS [47, 48] is taken as the knowledge engineering methodology in this study, which includes three main steps.

The first step is Knowledge Identification. Literatures of the domain are reviewed and analysed, and also existing knowledge models or semantic sources are surveyed in this step. The main outcomes are identifying the problems in the domain, the purpose of the knowledge model, and the scope of the model. At the end of this step, all the necessary terms of domain are elicited and a glossary of these terms is constructed. For instance, the values of embodied energy and CO_2e as well as parameters of concrete applied in this study are chosen from ICE database and BS 8500 Standard. The second step is Knowledge Specification. The main task in this step is to construct a specification of the knowledge model. Basically it involves choosing a template and then building up a semi-formal modelling which can be undertaken using any modelling language such as the UML in this case. The re-usable resources identified in the first step are also taken into consideration when construct the model. The last step is Knowledge Refinement, which is the final step of knowledge modelling. Two main tasks are undertaken, knowledge model validation and refinement. The refinement is a completion of knowledge modelling. The entire process normally will be repeated several times and each step is also an iterative process. In addition, developing a prototype is always recommended before the development of full version of knowledge model.

From the literature review, there are many methodologies for ontology development [49, 50]. Ontology Development 101 [51] is one of the most widely used guides for this purpose. It provides the methodology that develops ontology from either scratch or existing semantic resource. Therefore, an extended methodology based on Ontology Development 101 is applied in this study as the ontology engineering methodology. There are 9 key steps to develop OntoSCS ontology, which are:

Step 1. Determine the domain and scope of the ontology

Before creating a new ontology, the purpose and scope of ontology have to be determined by considering the current application and potential extensibility in the future. Because the scope of the ontology is a very important factor that affects the quality of ontology, competency questions are very essential as a method at the beginning stage of development to ensure the quality of ontology. Competency questions are normally just a sketch instead of exhaustive questions. Therefore the form of questions could be either open or closed-answer questions. Basically any kind of question related to the ontology could be regarded as a competency question. Typically in the early stage of an ontology development process, these questions will be asked using very straightforward natural language to test whether the ontology contains enough information or a particular level of detail is required, for example:

- Q: Why building this ontology?

  A: To manage multi-domain knowledge, to help engineer with repeating work, and provide them with structural optimised and sustainable design alternatives.

- Q: What will this ontology be used for?

  A: To be used in a knowledge-based system for decision support in early stage of building design.

- Q: What are the domains this ontology will cover?

  A: Structural design and building sustainability (including embodied energy and CO_2e in building materials)

- Q: Who will use the ontology?

  A: Structural engineers.

- Q: Is the ontology a brand new one or an extended one of existing ontology?

  A: It is a new ontology using existing classification and structure of semantic source.

Ideally, the informal competency questions should also have hierarchy or be listed in a stratified way that the solutions of lower level questions are the requirements of higher level questions. For instance, there are four levels of competency questions given below to explain this stratified structure:

a. Q: What type of structure will be the case in this study?

   A: Reinforced concrete structure.

b. Q: Which stages of structure design should be involved in this ontology?

   A: Conceptual design and component design.

c. Q: To achieve structural feasibility and sustainability of reinforced concrete design, what factors should be considered in conceptual design stage?

   A: Material, structural form and dimension, distance of transport.

d. Q: How to measure the sustainability of materials?

   A: Embodied energy and CO_2e.

Asking competency questions and modifying scope of the ontology model are an iterated process. Some of these questions above could be asked at any time during the development of ontology in order to improve the quality of ontology as much as possible. The answers to these questions guided by the initial motivation will help the developers to identify the essential information to build this ontology without covering redundant domain knowledge.

Step 2. Consider reusing existing ontologies

One of the main benefits of ontology for knowledge management is its ability to share and exchange knowledge with other ontologies thanks to the interoperability of OWL language. Thus, instead of creating a new ontology from scratch, it is important to consider if there is any existing domain ontology or source to extend or refine for this specific task. So that this ontology could provide common understanding among multi-disciplinary participants, interact with other ontologies in this domain, or merge with others for more applications in the future.

In terms of the existing semantic sources for this case, the IFC schema by BuildingSMART has been regarded as primarily developed standard for exchanging and sharing of Building Information Models (BIM) to increase the productiveness of design, construction, and maintenance operations within the life cycle of buildings [42]. It offers an example of structuring concepts associated with building elements; however with limitations of rule restrictions. Thus, the OntoSCS ontology follows the IFC's way of organising concepts with adding more specific relationships and restrictions. Some of the concepts have been changed to more readable names. For example, the term ifcBeam in IFC representation is changed to Beam in this ontology. Additionally, existing classification in building construction domain such as Uniclass (Unified Classification for the Construction Industry) is partially used to share a common vocabulary library with other ontologies in this domain.

Step 3. Enumerate important terms in the ontology

The output of knowledge identification is a glossary of essential terms elicited from reviewed and analysed literatures of this domain. Therefore a comprehensive list of all the concepts related to reinforced concrete design and building sustainability is generated in this step. In this study, not only the terms, but also the values of embodied energy and carbon in different materials shown in Table 1 are imported from ICE database [21] to the ontology. Additionally, the information of material suppliers is collected from GreenBookLive website [52].

Step 4. Define the classes and the class hierarchy

A variety of methods is used to develop class hierarchy and each of them has its advantages and drawbacks[53]. Since the OntoSCS ontology is constituted from existing classification and IFC, the hierarchy of IFC is inherited. A top-down development process is applied, where the most general concepts in the domain are defined before specifying the subclass concepts. In this ontology, the general concepts include Product, Material Definition, and Resource Supplier, with a further breakdown of each general concept into more specific sub-concepts such as Building, Site, Material, and Material Constituent. All subclasses of a superclass inherit the properties of that class. For example, all the properties of Building Element will be inherited to all subclasses including Beam, Column, Slab and Foundation. Therefore a new property should be attached to most general class that can have that property. For instance, volume of structural element should be attached at the class Building Element instead of Column, since it is the most general class whose instance and subclasses will have volume.

Table 1
Embodied energy and carbon values of concrete materials in this study (ICE Database 2.0)

Material	Embodied Energy - MJ/kg			Embodied Carbon - $kgCO_2e/kg$		
% Cement Replacement - Fly Ash	0% (CEM I)	15%	30%	0% (CEM I)	15%	30%
GEN 0 (6/8 MPa)	0.55	0.52	0.47	0.076	0.069	0.061
GEN 1 (8/10 MPa)	0.70	0.65	0.59	0.104	0.094	0.082
GEN 2 (12/15 MPa)	0.76	0.71	0.64	0.114	0.105	0.093
GEN 3 (16/20 MPa)	0.81	0.75	0.68	0.123	0.112	0.100
RC 20/25 (20/25 MPa)	0.86	0.81	0.73	0.132	0.122	0.108
RC 25/30 (25/30 MPa)	0.91	0.85	0.77	0.140	0.130	0.115
RC 28/35 (28/35 MPa)	0.95	0.90	0.82	0.148	0.138	0.124
RC 32/40 (32/40 MPa)	1.03	0.97	0.89	0.163	0.152	0.136
RC 40/50 (40/50 MPa)	1.17	1.10	0.99	0.188	0.174	0.155
PAV1	0.95	0.89	0.81	0.148	0.138	0.123
PAV2	1.03	0.97	0.89	0.163	0.152	0.137

% Cement Replacement - GGBS	0% (CEM I)	25%	50%	0% (CEM I)	25%	50%
GEN 0 (6/8 MPa)	0.55	0.48	0.41	0.076	0.060	0.045
GEN 1 (8/10 MPa)	0.70	0.60	0.50	0.104	0.080	0.058
GEN 2 (12/15 MPa)	0.76	0.62	0.55	0.114	0.088	0.065
GEN 3 (16/20 MPa)	0.81	0.69	0.57	0.123	0.096	0.070
RC 20/25 (20/25 MPa)	0.86	0.74	0.62	0.132	0.104	0.077
RC 25/30 (25/30 MPa)	0.91	0.78	0.65	0.140	0.111	0.081
RC 28/35 (28/35 MPa)	0.95	0.83	0.69	0.148	0.119	0.088
RC 32/40 (32/40 MPa)	1.03	0.91	0.78	0.163	0.133	0.100
RC 40/50 (40/50 MPa)	1.17	1.03	0.87	0.188	0.153	0.115
PAV1	0.95	0.82	0.70	0.148	0.118	0.088
PAV2	1.03	0.91	0.77	0.163	0.133	0.100

Step 5. Define the properties of classes

Since the class hierarchy itself is not enough to represent domain knowledge, the internal structure of concepts has to be considered. As some of the terms or concepts from the glossary have been selected as classes in step 4, most of the remaining terms could be represented as properties in ontology. There are three types of properties used in this case: object property, data-type property and annotation property. The object property defines the relationship between various concepts, for example, isLocatedat and isSupplierOf. Connections between classes are established through these object properties. Then the statements such as “Building isLocatedat ConstrcutionSite” and “ResourceSupplier isSupplierOf Material” could be formulated. The data-type property defines quantitatively and qualitatively characteristics of instances of classes. Common value types include String, Number, Boolean and Enumerated can be filled in the data-type property. For instance, a resource supplier has an address “Coldharbour Lane”. In OntoSCS ontology, it can be represented as: an instance of ResourceSupplier class has a data-type property called “Address” with data value “Coldharbour Lane”. Essential data-type properties such as TotalECO2e, CompanyName and Volume are populated under corresponding classes. The annotation property is text comment on some elements of ontology, which is used to clarify data and explanation.

Step 6. Define the facets

Facets indicate the value of a property, the cardinality of the property value and the class that the property attached to. Either qualitative or quantitative values could be defined to the property. For example, the Rating of ResourceSupplier could be atrributed qualitatively using different levels of evaluation – good, very good and excellent. On the other hand, the distance from ResourceSupplier to ConstructionSite can be measured quantitatively using numbers such as 224.49 km.

Step 7. Create instances

In this step, individual instances of classes are created in the hierarchy. Defining an instance includes choosing a class, creating an individual instance of this class, and populating the values of properties. For example, the individual instances of ResourceSupplier class are a list of companies from GreenBookLive Responsible Sourcing. The name, address and other information of each company need to be manually filled in as the values of data-type properties. Similarly, the values of embodied energy and CO2e in Table 1 are populated into ontology as data-type properties of different concrete materials.

Step 8. Define SWRL rules

In addition to the properties defined in step 5, the computational and reasoning capabilities of SWRL rule provide a more flexible way to infer new properties based on existing ones.

Step 9. Define SQWRL rules

Using some built-in functions of SWRL such as sqwrl:select, it is efficient to define application oriented queries to interact with OntoSCS ontology, in order to obtain sensible results from knowledge model. The details of developing SWRL rules and SQWRL queries in step 8 and 9 are explained in rule-based system development part.

The main outcome of the former seven steps above is a sustainable reinforced concrete structure ontology knowledge model that can be used as the knowledge base for decision support system. To facilitate the visualisation of the knowledge model and preparation of formal ontology development, a semi-formal model involving all the concepts, properties and relationships is developed using Unified Modelling Language (UML). As illustrated in Fig. 2, concepts from structural design domain such as column, reinforcing bar and concrete are organised in a hierarchical structure, while the factors affecting sustainability including resource supplier, transport distance, material constituents are integrated into this hierarchy in different forms. In addition to the subsumption relations that exist between the top level classes and subclasses, the object properties including their multiplicities have been used to relate the top level concepts. For example the multiplicity of 1…* on the object property "isSupplierOf" that relates the ResourceSupplier and MaterialDefinition means one or more products are supplied by the resource supplier. Taking the UML diagram as a reference, OntoSCS knowledge model is manually edited in Protégé-OWL 3.5 following the ontology guide 101. Fig. 3 presents the implementation results in software environment of Protégé-OWL 3.5.

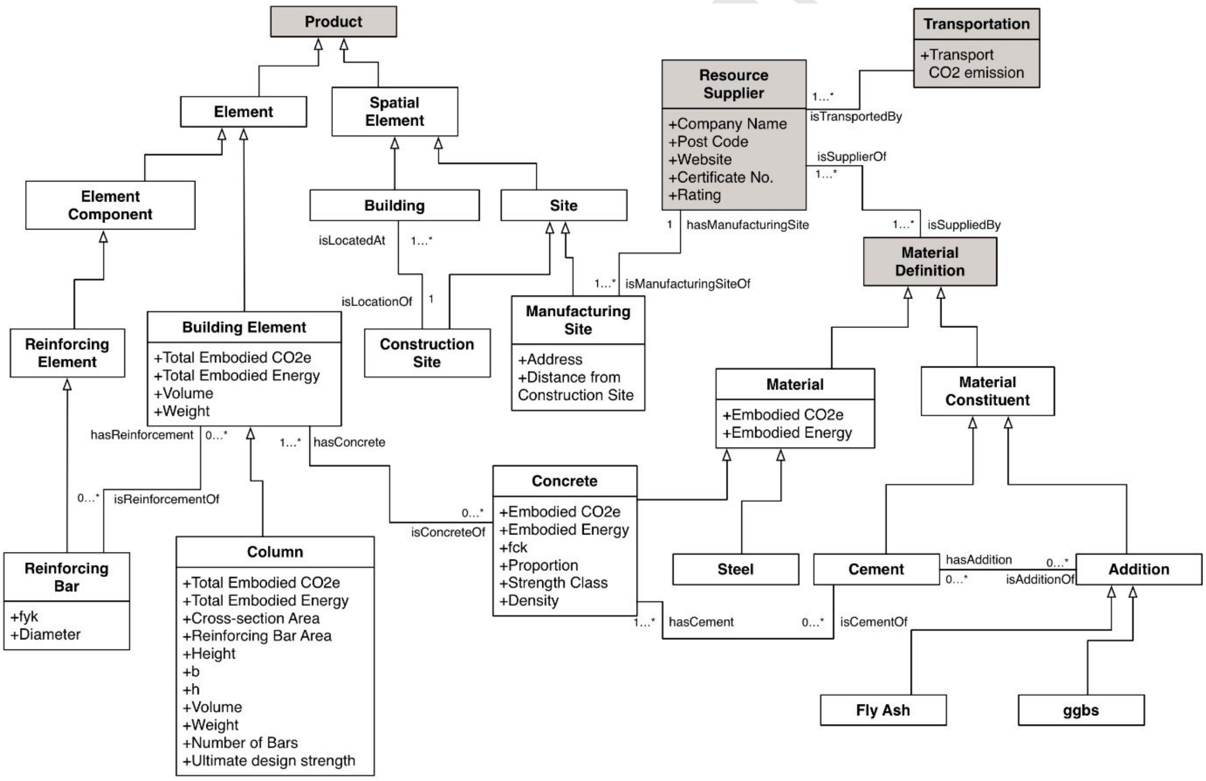

Fig. 2. UML class diagram of key concepts of OntoSCS ontology.

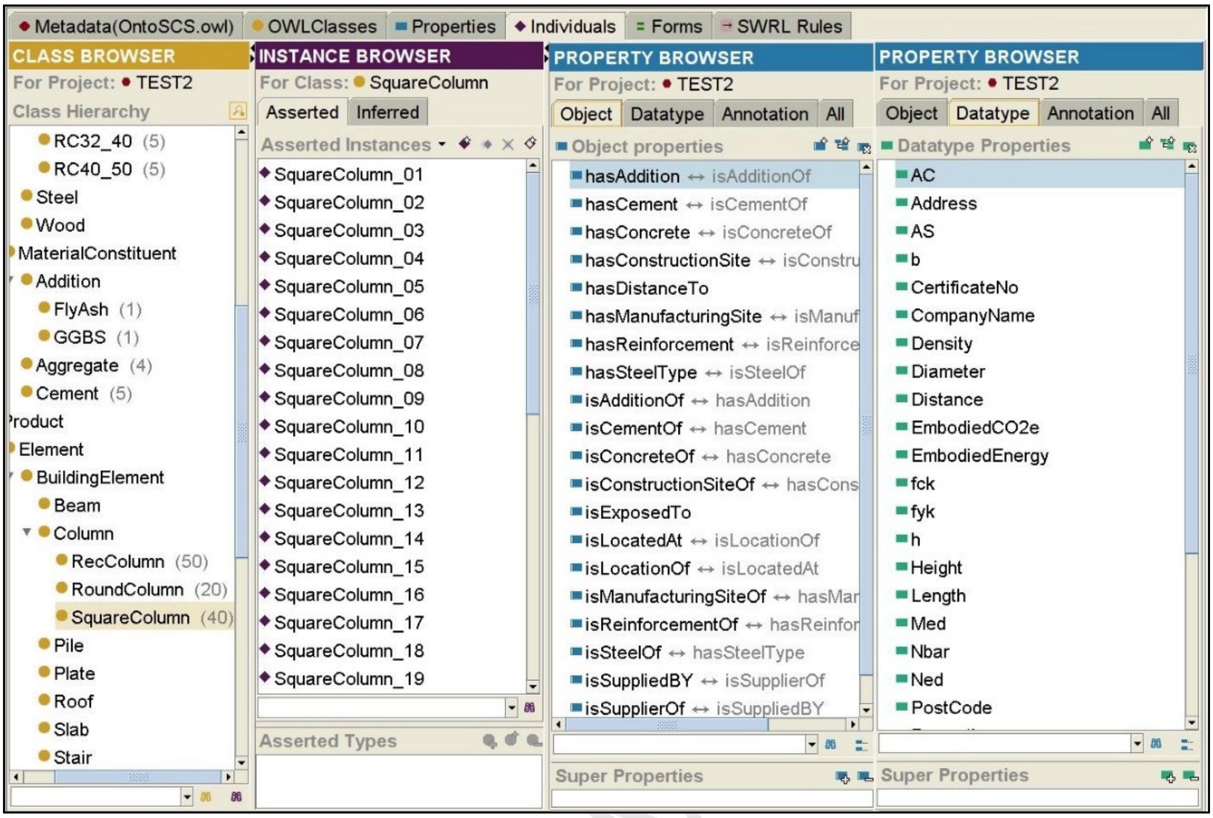

Fig. 3. OntoSCS ontology development in Protégé-OWL 3.5.

4.2.2 Ontology validation

A major recommendation by most methodologies is the validation of any ontology knowledge base. This activity consists of ensuring the semantic correctness, the syntactic correctness and also to verify if the ontology meets the requirement conditions or does what it was intended to do. In this section the first two validation activities will be examined and a case study based validation will be presented in Section 5.

Semantic validation

In terms of semantic validation, two main methods can be applied depending on the ontology development approaches. The first method is manual validation by consulting domain experts and checking the concepts in proposed ontology model, if the ontology is developed from scratch. The accuracy of this method is high yet with some drawbacks such as time consuming and cost [54]. In the second method, ontology alignment, merging or comparison techniques can be used for semantic validation, if the ontology is developed based on re-using existing ones [55-57]. In this method, the proposed ontology is aligned or compared to another one which is often referred to as a reference or a golden standard [56, 57], in order to find corresponding concepts that have same intended meaning. If the whole re-used ontology has been adopted without modification, then the new one can be regarded as validated. Otherwise, a new ontology that partially re-uses existing ontologies needs to be validated by both expert reviews and ontology alignment. Based on the fact that the top level concepts of the OntoSCS ontology are mainly from IFC instead of arising from existing ontologies, each concept is analysed and semantically validated manually by domain experts.

Syntactical validation

After semantically validating the ontology, it is imperative to syntactically check its consistency. The developed ontology is checked against subsumption, equivalence, instantiation and consistencies [58]. Currently, there are two major methods of performing consistency checking of an ontology [55], i.e. manually and automatically. Automatic validation is achieved through the use of reasoners such as Pellet. It is a plug-in incorporated in Protégé-OWL 3.5, which is applied to illustrate the errors in the syntax of ontology. Elimination of anomalies in the ontology can be conducted according to the error messages from reasoner. A completed consistency checking OntoSCS ontology is shown in Fig. 4. After the syntactic verification, the ontology needs to be validated for the purpose for which it was developed. In Section 5, a case study with three applications is established to test if the OntoSCS ontology works as intended.

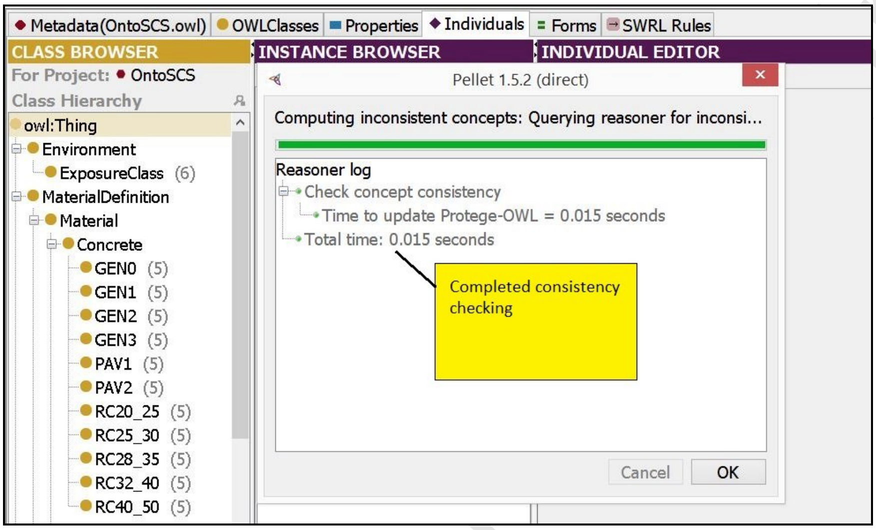

Fig. 4. Consistency checking result of OntoSCS ontology.

4.2.3 Development of rules

For the realisation of the Semantic Web, the integration of different layers of its conceived architecture is a fundamental issue. In particular, the integration of rules and ontologies is currently under investigation, and many proposals in this direction have been made. They range from homogeneous approaches, in which rules and ontologies are combined in the same logical language (e.g., in SWRL and DLP), to hybrid approaches, in which the predicates of the rules and the ontology are distinguished and the suitable interfacing between them is facilitated [38]. In this study, one of the homogeneous approaches is adapted, which provides a seamless semantic integration of rules and ontologies; more importantly, a reasoning function of deducting new facts based on existing ones.

In this method, both ontologies and rules are embedded in a common logical language - OWL. Because SWRL is built on the top of OWL, the interaction between them is based on tight semantic integration. Therefore there is no distinction between rule predicates and ontology predicates. Rules could be used for defining both classes and properties of the ontology.

The development of rules for OntoSCS ontology is in SWRLTab environment of Protégé-OWL 3.5. There are used two types of semantic rules. SWRL rules type is used for reasoning function. SQWRL (Semantic Query-Enhanced Web Rule Language), a SWRL-based rule language, is used for querying OWL ontologies. As introduced in Section 3, SWRL syntax contains two main parts, the antecedent and consequent that are associated using implication symbol →. Each of them is a conjunction of

atoms that are connected using conjunction symbol ∧. Seven types of atoms are provided by SWRL:

Class atoms, Individual Property atoms, Data Valued Property atoms, Different Individuals atoms, Same Individual atoms, Built-in atoms and Data Range atoms. The variables in each atoms are represented by the interrogation identifier ?. A Class atom consists of a named class in OWL ontology with a variable or a named class with an individual in OWL ontology. An Individual Property atom consists of an object property in OWL ontology and two variables representing two individuals in OWL ontology. Similarly, a Data Valued Property atom consists of data property in Owl ontology and two variables, first representing an OWL individual and second a data property or value. Different Individuals atoms and Same Individual atoms are used to distinguish if two variables are same OWL individuals or not. Built-in atoms is one of the most advanced features offered by SWRL because of its ability to support more complex predicates including common mathematical operations. Table 2 explains the meaning and function of each atom in an example SWRL rule implemented in this study. The example rule written in SWRL is:

Rule 1

```
Column(?C) ∧ Volume(?C, ?CV) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ EmbodiedCO2e(?Con, ?ECO2) ∧
swrlb:multiply(?TECO2, ?CV, ?ECO2) → TotalECO2e(?C, ?TECO2)
```

Rule 1 implies that the total embodied CO_2e (TotalECO2e) of the column (Column) with a certain type of concrete (hasConcrete) equals the volume of column (Volume) multiplied the amount of embodied CO_2e per unit volume (EmbodiedCO2e). The calculation is achieved using SWRL built-in swrlb:multiply. Another example demonstrating SQWRL use is, for instances:

Query 1

```
Column(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ swrlb:greaterThan(?Confck, 30) →
sqwrl:select(?C, ?Confck)
```

The meaning of Query 1 is if there is a column with concrete strength (fck) higher than 30 N/mm^2, then select this column and display the name and strength. The comparison and selection functions are achieved using SWRL built-ins swrlb:greaterThan and sqwrl:select respectively. A set of SWRL and SQWRL rules has been developed and incorporated into the OntoSCS ontology for specific applications as shown in Fig. 5. More example rules are presented in the case studies of the following section.

Table 2
Examples of atoms in SWRL rules

Atom type	Atom	Corresponding OWL element
Class atom	Column(?C)	Column (class)
	Concrete(?Con)	Concrete (class)
Data Valued Property atom	Volume(?C, ?CV)	Volume (data-type property)
	EmbodiedCO2e(?Con, ?ECO2)	EmbodiedCO2e (data-type property)
	TotalECO2e(?C, ?TECO2)	TotalECO2e (data-type property)
	fck(?Con, ?Confck)	Fck (data-type property)
Individual Property atom	hasConcrete(?C, ?Con)	hasConcrete (object property)
Built-in atom	swrlb:multiply(?TECO2, ?CV, ?ECO2)	
	swrlb:greaterThan(?Confck, 30)	
	sqwrl:select(?C, ?Confck)	

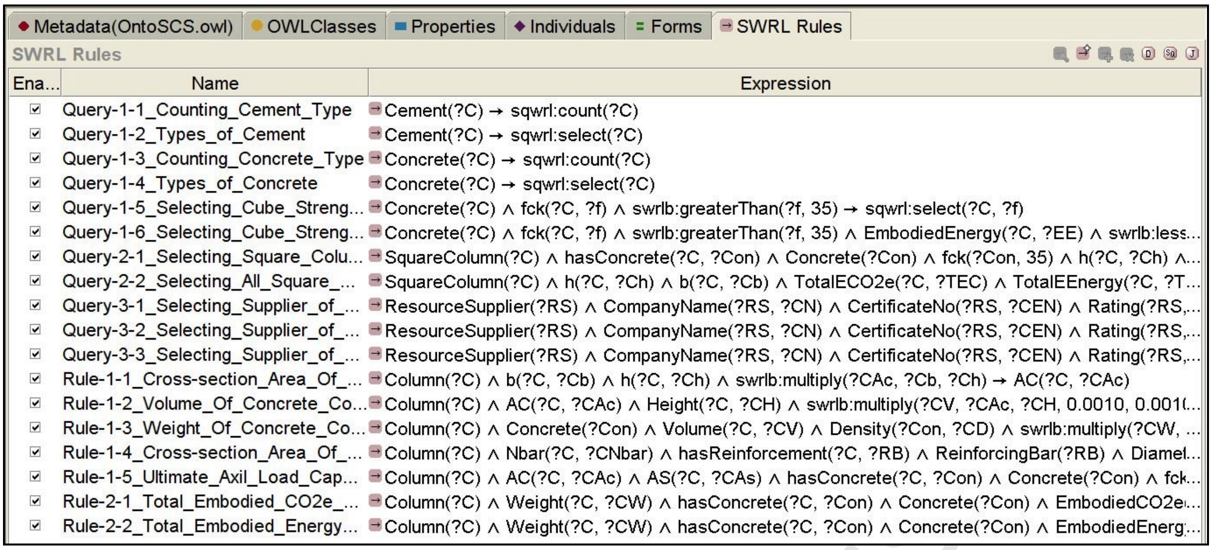

Fig. 5. SWRL rules and SQWRL queries in OntoSCS.

5. Case study validation of OntoSCS system

5.1 Case study description

In this section, a reinforced concrete column design case is taken to validate the OntoSCS system and to demonstrate how this system works for sustainable structural design. A continuous reinforced concrete column of height H = 4 m with a rectangular cross-section of area bh, where b is the width and h is the length, is considered. The column is assumed to have an axial load of Nu = 4500kN. Defining a feasible solution as one that satisfies requirements and restrictions from Eurocode 2, the objective is to determine the feasible structural design that minimises the total embodied energy and carbon.

The initial design variables are the width and length of the column “b” and “h”; the number of reinforcing bars “Nbar”; the height of the column “Height”; and the types of concrete and reinforcement. The OntoSCS ontology involves 110 types of columns as predefined instances with different initial variables. The total area of the longitudinal reinforcement “As”, the total area of the cross-section of column “Ac” and total volume of the column are not given specific values as they are deducted by the rules defined in ontology. Based on the analysis of design code and literature of sustainable building, the initial design variables are manually edited into OntoSCS as different classes, object properties, data properties and instances of classes. The knowledge concepts and corresponding objects in OntoSCS are presented in Fig. 6. There are 50 square columns with different dimensions, concrete grades and cement additions as instances of this case. By executing the SQWRL query applied in this case study, any column that meets the specific structural feasible requirements will be selected by the system as a candidate of column design solution. After a comparison of all candidates, the one with minimum embodied energy and carbon is regarded as the most sustainable design solution.

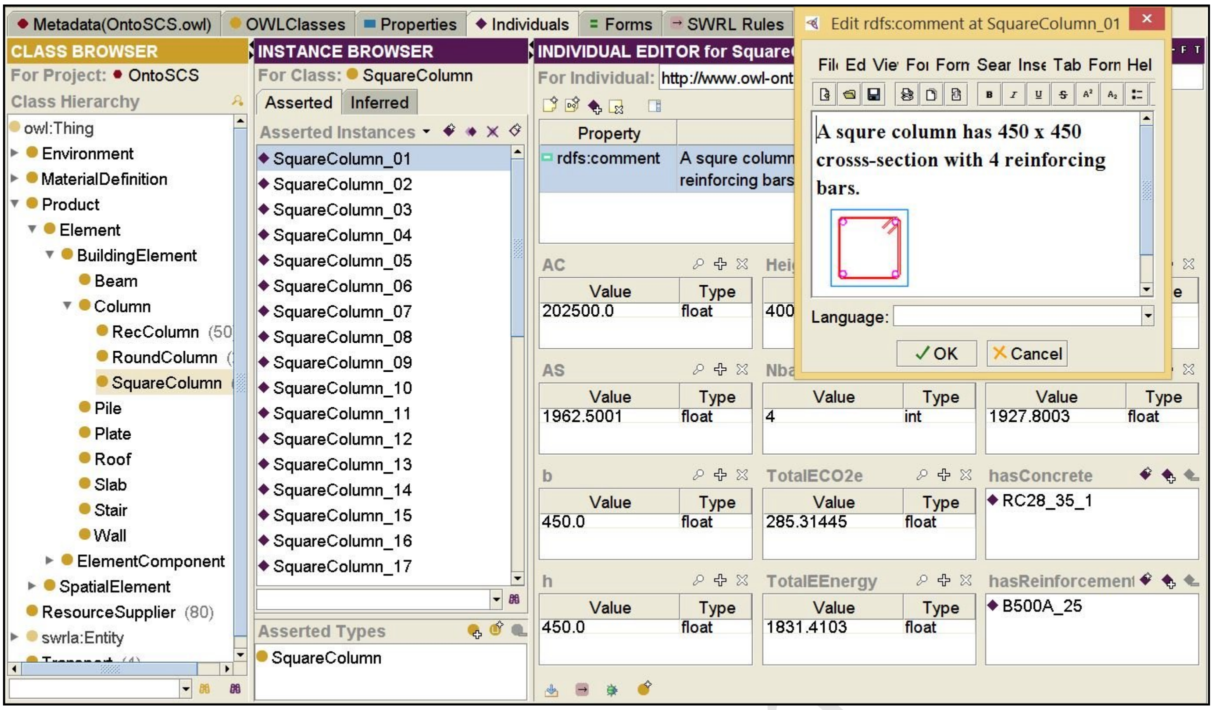

Fig. 6. Knowledge concepts of OntoSCS column case study.

In this study, basic equations in design code to calculate structural load capacity as well as embodied energy and carbon are converted into the form of semantic rules. The rules implemented in this case are shown below as examples:

Rule 1-1. The total area of the cross-section of column A_C

$A_c = b \times h$
Column(?C) ∧ b(?C, ?Cb) ∧ h(?C, ?Ch) ∧ swrlb:multiply(?CAc, ?Cb, ?Ch) → AC(?C, ?CAc)

Rule 1-2. Calculating volume of concrete column

$Volume = A_c \times Height$
Column(?C) ∧ Ac(?C, ?CAc) ∧ Height(?C, ?CH) ∧ swrlb:multiply(?CV, ?CAc, ?CH, 0.0010, 0.0010, 0.0010) → Volume(?C, ?CV)

Rule-1-3. Calculating weight of concrete column

$Weight = desity \times volume$
Column(?C) ∧ Volume(?C, ?CV) ∧ Density(?C, ?CD) ∧ swrlb:multiply(?CW, ?CV, ?CD) → Weight(?C, ?CW)

Rule 1-4. The total area of the longitudinal reinforcement A_S

$A_s = \frac{D}{2} \times \frac{D}{2} \times \pi \times N_{bar}$
Column(?C) ∧ Nbar(?C, ?CNbar) ∧ hasReinforcement(?C, ?RB) ∧ ReinforcingBar(?RB) ∧ Diameter(?RB, ?RBD) ∧ swrlb:multiply(?CAs, ?CNbar, ?RBD, ?RBD, 3.14, 0.25) → AS(?C, ?CAs)

Rule 1-5. The ultimate axial load of a column

$$N_{ed} = 0.567 f_{ck} A_c + 0.87 A_s f_{yk}$$

Column(?C) ∧ AC(?C, ?CAc) ∧ AS(?C, ?CAs) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ hasReinforcement(?C, ?SB) ∧ ReinforcingBar(?SB) ∧ fyk(?SB, ?SBfyk) ∧ swrlb:multiply(?x, 0.576, ?Confck, ?CAc) ∧ swrlb:multiply(?y, 0.87, ?CAs, ?SBfyk) ∧ swrlb:add(?CNed, ?x, ?y) →
Ned(?C, ?CNed)

Rule 2-1. The total embodied carbon of the column

$$Total\ Embodied\ CO2e = Volume \times ECO2e\ per\ unit$$

Column(?C) ∧ Volume(?C, ?CV) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ EmbodiedCO2e(?Con, ?ECO2) ∧

swrlb:multiply(?TECO2, ?CV, ?ECO2) →
TotalECO2e(?C, ?TECO2)

Rule 2-2. The total embodied energy of the column

$$Total\ Embodied\ Energy = Volume \times EEnergy\ per\ unit$$

Column(?C) ∧ Weight(?C, ?CW) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ EmbodiedEnergy(?Con, ?EE) ∧ swrlb:multiply(?TEE, ?CW, ?EE) →
TotalEEnergy(?C, ?TEE)

Rule 1-1 to Rule 1-5 are applied to calculate the structural characteristics of columns while Rule 2-1 and Rule 2-2 to calculate the total amount embodied energy and carbon in columns respectively. Based on existing facts defined in ontology knowledge base, the OntoSCS system infers new facts by executing rule set and populates new facts back into the ontology. Fig. 7 takes one of the columns as an example to demonstrate the initial and inferred facts in different colour marks respectively.

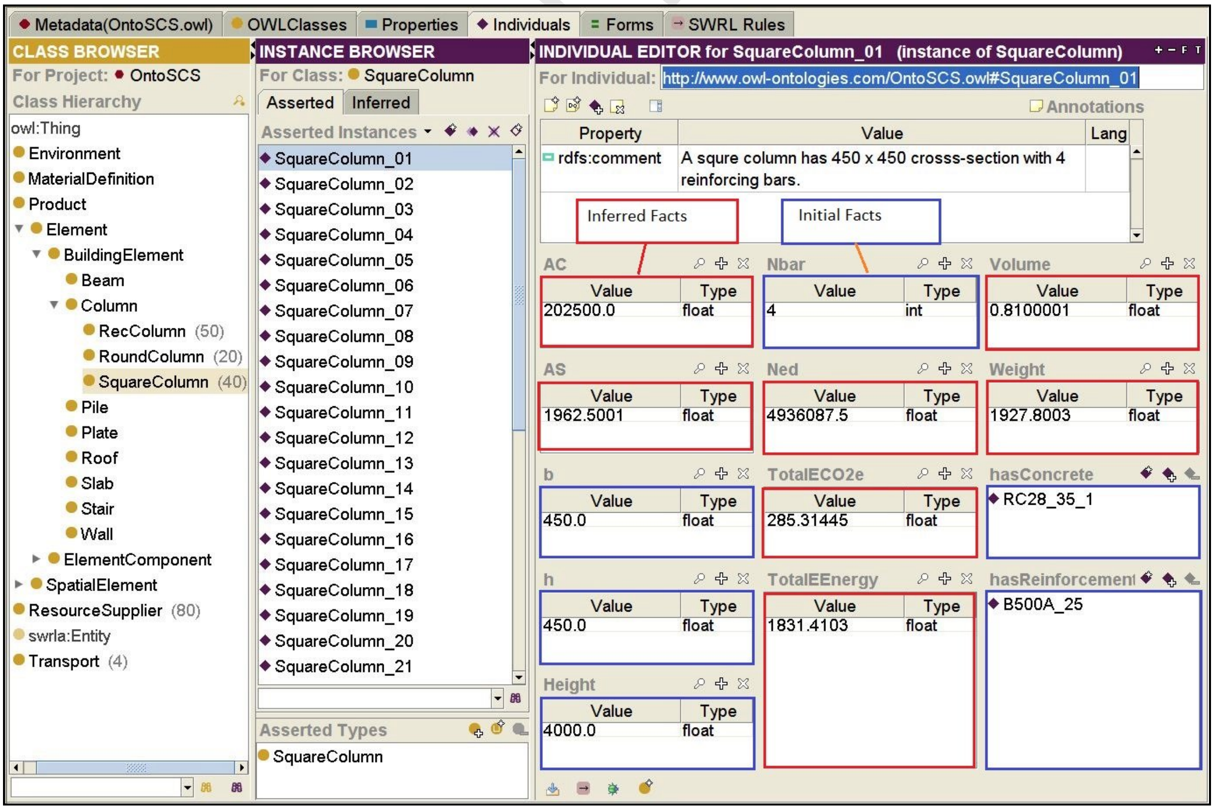

Fig. 7. Inferred facts based on existing facts in OntoSCS ontology.

5.1.1 Application 1. The use of OntoSCS in selection of columns with different cement additions.

Based on the ontology model developed in case study, various applications are tested using different SQWRL queries. In the first application, the dimension of column 450x450 and concrete type RC28/35 have been determined up front. Thus the next step is to determine the constraint of selection. The axial load of Nu=4500kN is chosen as a constraint that any column in OntoSCS ontology has higher or equal axial load capacity would be a candidate design solution. This constraint has been modelled using the SWRL built-in and is represented as swrlb:greaterThanOrEqual(?x, 4500). This built-in is combined with other SWRL syntax to form an SQWRL query represented in Query 2-1.

Query 2-1. Select square columns using RC28/35 with load capacity larger than 4500kN.

```
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, 35) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧

TotalEEnergy(?C, ?TEE) ∧ TotalECO2e(?C, ?TEC) ∧ Ned(?C, ?CN) ∧ swrlb:greaterThanOrEqual(?CN, 4500000) →

sqwrl:select(?C, ?Ch, ?Cb, ?CN, ?TEE, ?TEC)
```

Fig. 8 demonstrates the execution and results in SWRLTab. The outputs from OntoSCS ontology are presented and compared in Table 3, which 5 columns with different cement additions are capable to support the design load. The total amounts of embodied energy and carbon of each column are compared. From the results, it is apparent that column made of ready-mix concrete with 50% GGBS addition has minimum embodied energy and carbon, being recommended to be used in the structural design.

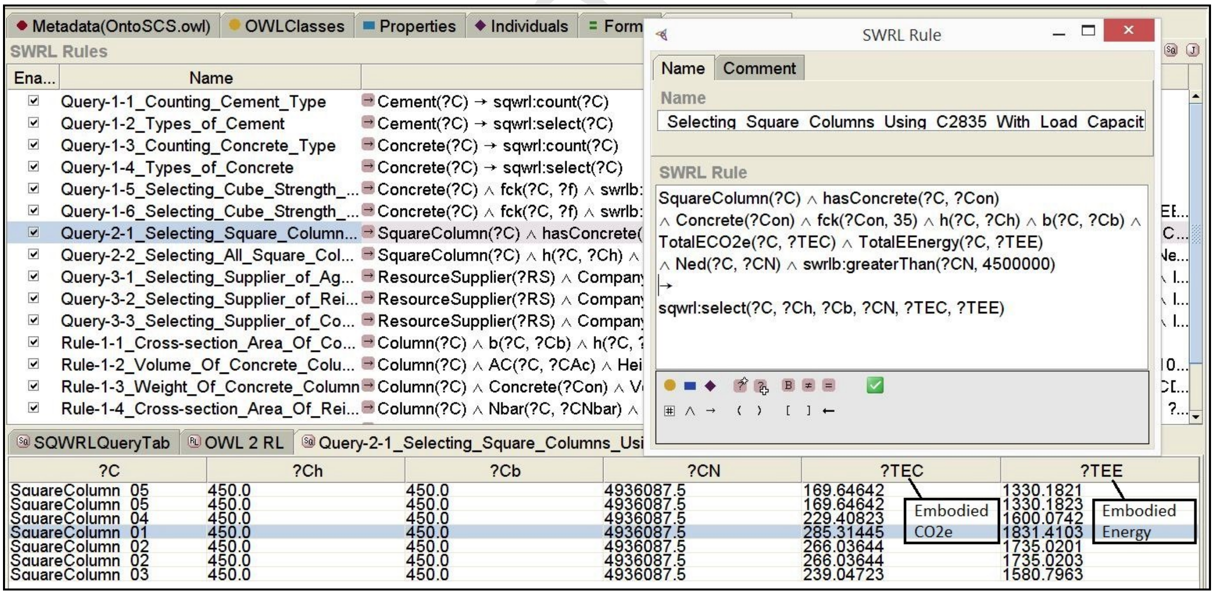

Fig. 8. Execution and results of Query 2-1 for column selection.

Table 3
Comparison of selected columns

Column No.	Addition Proportion	Dimension (mm)	Strength Class	Axial Load (kN)	Embodied Energy (MJ)	Embodied Carbon ($kgCO_2e$)
SqaureColumn_01	0%	450 × 450	C28/35	4936.1	1831.4	285.3
SqaureColumn_02	15% Fly ash	450 × 450	C28/35	4936.1	1735	266

SqaureColumn_03	30% Fly ash	450 × 450	C28/35	4936.1	1580.8	239
SqaureColumn_04	25% GGBS	450 × 450	C28/35	4936.1	1600.1	229.4
SqaureColumn_05	50% GGBS	450 × 450	C28/35	4936.1	1330.2	169.6

In this application, only the type and proportion of cement additions are taken as variables in columns selection. In practice, the situation is more complex as it is possible to use higher grade concrete or change the dimension of column to meet the requirements of structural feasibility. As a consequence, the amount of embodied energy and carbon in columns may change as well. A more comprehensive application is examined in the following part.

5.1.2 Application 2. OntoSCS design selection of columns with various dimensions and concretes.

In this application, two more variables, column dimensions and concrete grade, are taken into consideration to conduct a more comprehensive and practical column selection. The axial load of Nu = 4500kN is still chosen as the constraint. By running query 2-2, all the columns with axial load capacity that is larger than 4500kN are selected. The output of executing query 2-2 is presented in Fig. 9 and the results are compared in Table 4.

Query 2-2. Select square columns with load capacity larger than 4500kN.

SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ TotalEEnergy(?C, ?TEE) ∧ TotalECO2e(?C, ?TEC) ∧ Ned(?C, ?CN) ∧

swrlb:greaterThanOrEqual(?CN, 4500000) →
sqwrl:select(?C, ?Ch, ?Cb, ?CN, ?TEE, ?TEC)

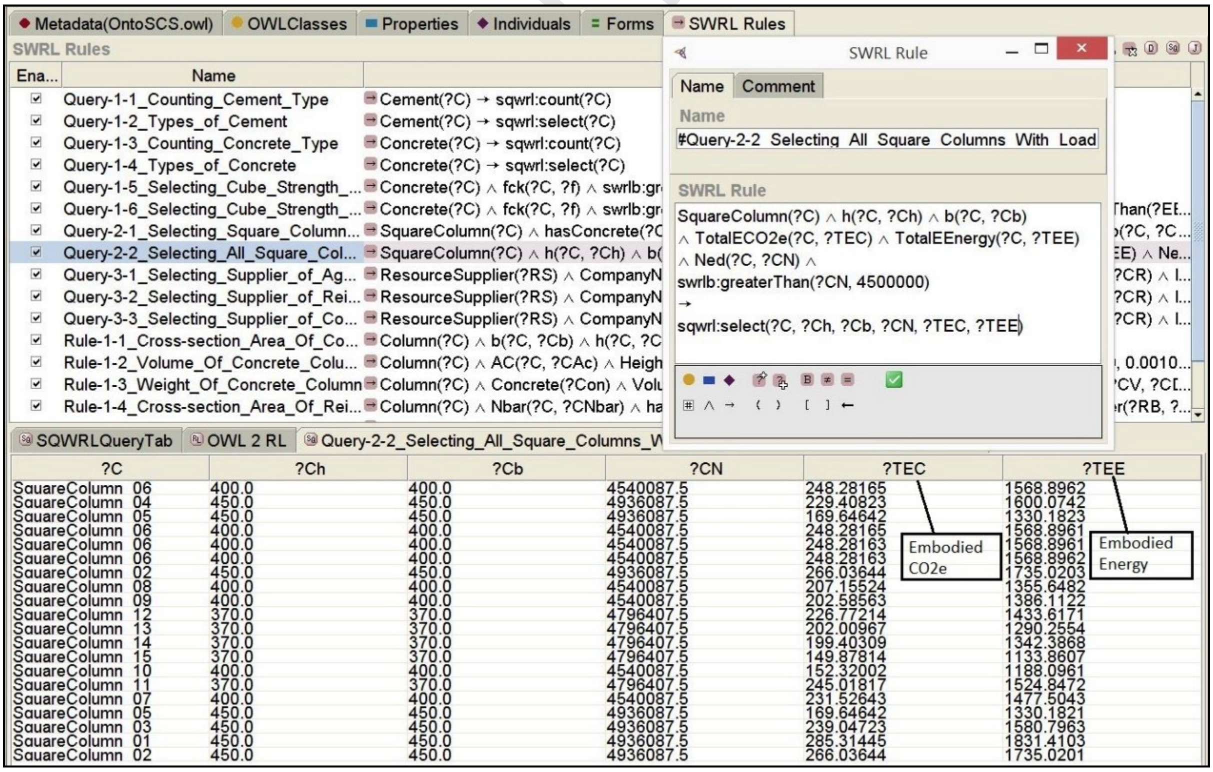

Fig. 9. Execution and results of Query 2-2 for column selection.

Table 4
Comparison of selected columns

Column No.	Addition Proportion	Dimension (mm)	Strength Class	Axial Load (kN)	Embodied Energy (MJ)	Embodied Carbon ($kgCO_2e$)
SqaureColumn_01	0%	450 × 450	C28/35	4936.1	1831.4	285.3
SqaureColumn_02	15% Fly ash	450 × 450	C28/35	4936.1	1735	266
SqaureColumn_03	30% Fly ash	450 × 450	C28/35	4936.1	1580.8	239
SqaureColumn_04	25% GGBS	450 × 450	C28/35	4936.1	1600.1	229.4
SqaureColumn_05	50% GGBS	450 × 450	C28/35	4936.1	1330.2	169.6
SqaureColumn_06	0%	400 × 400	C32/40	4540.1	1568.9	248.3
SqaureColumn_07	15% Fly ash	400 × 400	C32/40	4540.1	1477.5	231.5
SqaureColumn_08	30% Fly ash	400 × 400	C32/40	4540.1	1355.6	207.2
SqaureColumn_09	25% GGBS	400 × 400	C32/40	4540.1	1386.1	202.6
SqaureColumn_10	50% GGBS	400 × 400	C32/40	4540.1	1188.1	152.3
SqaureColumn_11	0%	370 × 370	C40/50	4796.4	1524.8	245
SqaureColumn_12	15% Fly ash	370 × 370	C40/50	4796.4	1433.6	226.8
SqaureColumn_13	30% Fly ash	370 × 370	C40/50	4796.4	1290.3	202
SqaureColumn_14	25% GGBS	370 × 370	C40/50	4796.4	1342.4	199.4
SqaureColumn_15	50% GGBS	370 × 370	C40/50	4796.4	1133.9	149.9

From the result, 15 design alternative solutions out of 50 square columns have enough strength to afford the given load and meet the requirements and constrains from structural design code, which means the requirements of structural feasibility are fulfilled. In terms of sustainability, typically a reduction in concrete strength class will offer immediate savings in terms of embodied energy and carbon (because of reduced cement usage). However, the Fig. 10 indicates that, for this concrete column design scenario, the higher strength concrete class would afford element size reductions and therefore a decrease of corresponding total embodied energy and CO_2e. In other word, the increase of embodied energy and CO_2e caused by higher concrete strength class is offset against a more slender structural element providing less amount of concrete and cement usage. Thus, the results indicate that an optimised structural member design results in decreases of 14.8% of embodied CO_2e (comparing Column 450×450 with Column 370×370). In the aspect of cost, according to the data from Spon's Civil Engineering and Highway Works Price Book, using column with RC40/50 also gains more cost benefits by up to 25.1% than column with RC28/35.

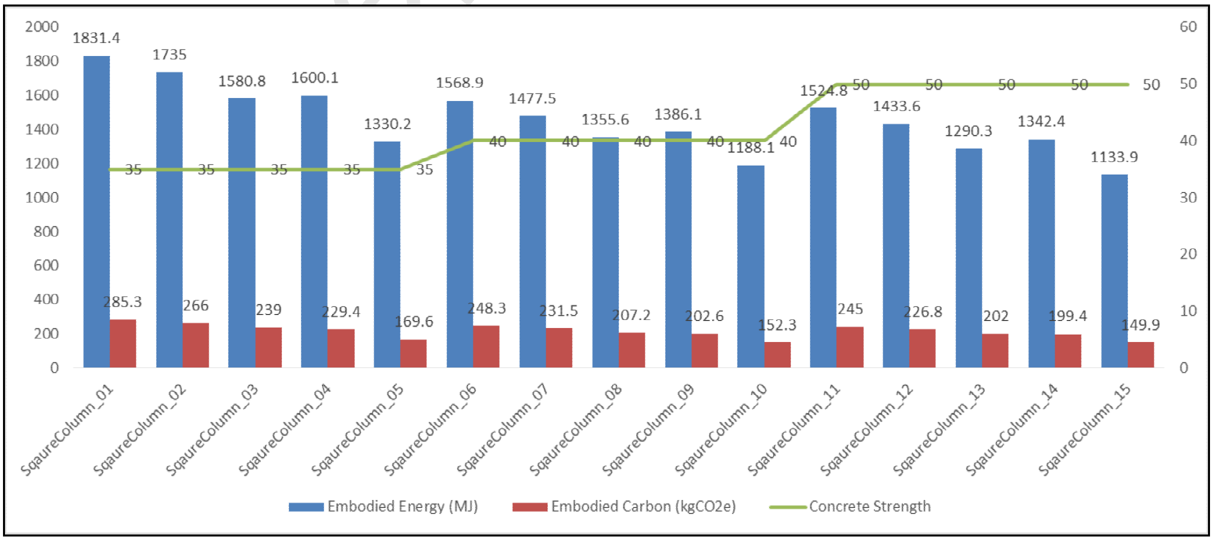

Fig. 10. Comparison of selected columns with different cement additions and structural dimensions.

5.1.3 Application 3. Selection of structural material suppliers

In addition to the selection of less embodied energy and carbon material or structural form demonstrated in application 1 and 2, the selection of material supplier also significantly affects sustainability of building. In this application, OntoSCS is used to find a certificated responsible sourcing of construction products. Query 3-3 explains the semantic relationships between the construction materials, construction site, supplier and manufacture site in OntoSCS ontology. By using the object property isSupplierOf, individual instances of ResourceSupplier class are captured. The output of executing query 3-3 is presented in Fig. 11, where 8 suppliers with different distances to construction site and product sustainable ratings are selected by the system. According to the results given by OntoSCS, the supplier of materials used in this construction project could be decided based on distance or product rating, in order to minimise the embodied energy and carbon consumption caused by transport.

Query 3-3. Selecting all the suppliers that provide concrete product, and showing the Responsible Source Rating and distance between manufacture site and construction site.

ResourceSupplier(?RS) ∧ CompanyName(?RS, ?CN) ∧ CertificateNo(?RS, ?CEN) ∧ Rating(?RS, ?CR) ∧ Postcode(?RS, ?PC) ∧ hasManufacturingSite(?MS) ∧ Address(?MS, ?CA) ∧ Distance(?MS, ?CD) ∧ isSupplierOf(?RS, RC40_50_5) → sqwrl:select(?RS, ?CN, ?CEN, ?CR, ?CA, ?PC, ?CD) ∧ sqwrl:orderBy(?CD)

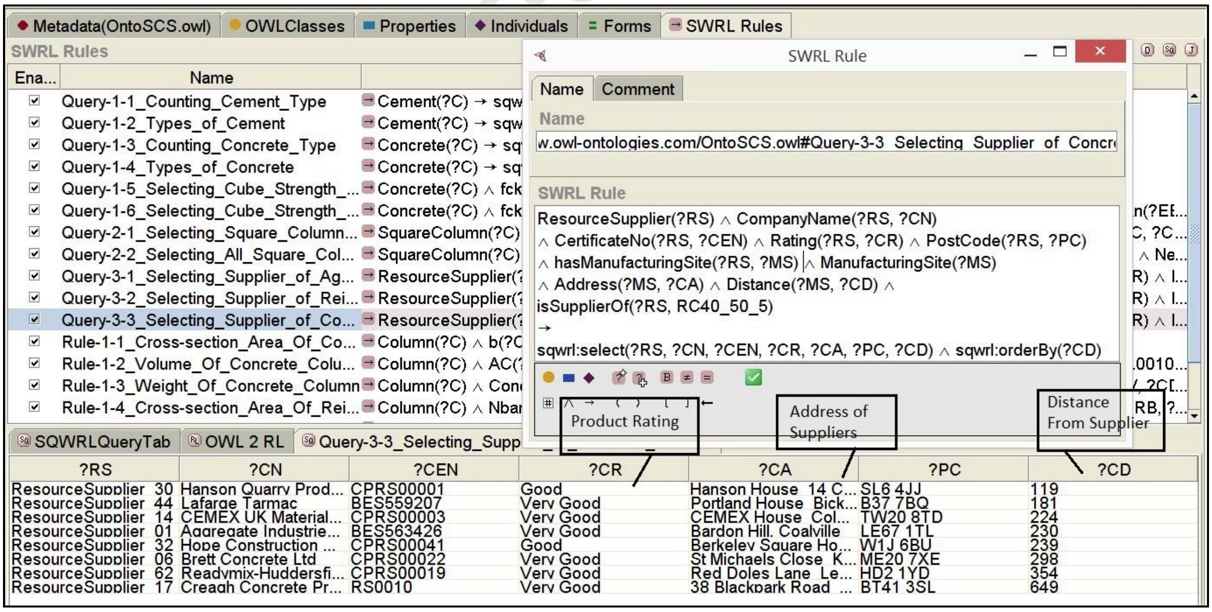

Fig. 11. Selected concrete suppliers from OntoSCS ontology.

6. Conclusion

In this paper, an ontology-based approach that helps structural engineer to design more environment friendly structural components is presented. The growing importance of considering sustainability in building structural design stage promotes the creation of our work. Despite being an initial exploratory study, this work is an important step towards exploring in greater detail the possibilities of implementing the Semantic Web technologies such as ontology and SWRL in building design and construction area. A prototypical system named OntoSCS has been developed and validated in this study. This system applies an effective way of managing both structural design and building sustainability knowledge by combining ontology and SWRL rules. With the capability of simultaneously computing structural load capacity as well as embodied energy and carbon, it could eventually assist structural engineers to understand the environmental impact of their designs and make better decisions in early stage of building design. By validating the OntoSCS system using case studies, the main objectives of this study have been accomplished.

Firstly, multiple domain knowledge including building structural design and sustainability has been modelled as formal structured ontology. It allows computer to process and draw meaningful conclusion form it. Consequently, the results obtained from validation process agree with structural design code and therefore can be used in real practice.

Secondly, an extension of this OWL ontology to include SWRL rules has been undertaken. A set of exemplary rules is presented to depict how decisions can be made based on the execution of the rules. SWRL rules incorporated in the OntoSCS ontology are used in (1) calculating load capacity of structural components, (2) calculating total values of embodied energy and carbon, (3) selecting structural members and material constituents, and (4) selecting suppliers of material.

Finally, although the OntoSCS system aims at facilitating decision making process for low embodied energy and carbon concrete structural design, the methodology adopted in this study is highly extensible and adaptable. Since the general concepts of this ontology are elicited from IFC which involves all types of structure, this method can also be applied to other types of structural materials or structural forms such as steel and timber. For example, the application of steel structure could be achieved by using same ontology engineering method to import steel structure design knowledge into this system. In addition, embodied energy and carbon are primarily used as indicators in this study to measure the sustainability of structure because of available accurate values of them in existing database. However, other factors related to sustainability such as U-value and thermal mass, can be potentially added in to system to represent more comprehensive situation in practice. Moreover, the methodology of developing OntoSCS system is applicable for ontology developments in other research areas of building domain, such as design regulation checking, construction quality checking and facility management. Therefore, the ontology proposed in this study is re-usable as a semantic resource for other applications in building construction industry. The interoperability and extensibility of ontology provide a solution that could integrate all phases of building life cycle allowing designers to take decisions from a holistic perspective.

As part of future research, it is interesting to explore more possibilities of implementing this methodology in other applications of AEC/FM domain. The advantage of ontology-based knowledge system could facilitate most decision making processes in building life cycle.

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