An ontology-based holistic approach for multi-objective sustainable structural design

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DECLARATION

This work has not been submitted in substance for any other degree or award at this or any other university or place of learning, nor is being submitted concurrently in candidature for any degree or other award.

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Abstract

Building construction industry has significant impact on sustainability. The construction, operation and maintenance of buildings account for approximately 50% of global energy usage and anthropogenic greenhouse gas (GHG) emissions. In recent years, the embodied energy and carbon are identified increasingly important in terms of sustainability throughout building life cycle. Incorporation of sustainable development in building structural design becomes undoubtedly crucial. The effective building design requires smart and holistic tools that can process multi-objective and inter-connected domain knowledge to provide genuine sustainable buildings.

With the advancement of information and communication technologies, various methods and techniques have been applied to accomplish the multiple objectives of sustainable development in building design. One of the most successful approaches is building information modelling (BIM), which requires further enhancement of interoperability. The emergence of Semantic Web technology provides more opportunity to improve the information modelling, knowledge management and system integration.

The research presented in this thesis investigates how ontology and Semantic Web rules can be used in a knowledge-based holistic system, in order to integrate information about structural design and sustainability, and facilitate decision-making in design process by recommending appropriate solutions for different use cases. A research prototype namely OntoSCS incorporating OWL ontology and SWRL rules has been developed and tested in typical structural design cases. The holistic approach considers five inter-connected dimensions of sustainability, including structural feasibility, embodied energy and carbon, cost, durability and safety. In addition, the selection of structural material supplier and criteria in sustainability assessment are taken into account as well. This research concludes that the Semantic Web technology can be applied to structural design at early stage to provide multi-criteria optimised solution. The methodology and framework employed in this study can be further adapted as a generic multi-criteria and holistic decision support system for other domains in construction sector.

Keywords: Ontology, Building Information Modelling (BIM), Sustainability, Integrated system, The Semantic Web, Building structural design

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Finally, I dedicate this thesis to my family. Pursuing my study would not have been possible without the unconditional love and support from my parents. I would like to thank my wife, Wenjing for the encouragement and great patience she has been giving me through this long journey.

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List of Abbreviation

AEC	Architectural, Engineering and Construction
BIM	Building Information Modelling
GHG	Greenhouse Gas
HTML	Hyper Text Markup Language
ICT	Information and Communication Technology
IFC	Industry Foundation Classes
ISO	International Organisation for Standards
KBS	Knowledge-based System
SD	Sustainable Development
OWL	Web Ontology Language
RDF	Resource Description Framework
STEP	Standard for The Exchange of Product model data
SWRL	Semantic Web Rule Language
UML	Unified Modelling Language
W3C	World Wide Web Consortium
WWW	World Wide Web
XML	Extensible Markup Language

List of Publications

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KASIM, T., LI, H. J., REZGUI, Y., BEACH, T. & HOU, S. A comparative study between traditional sustainability assessment methods, rules-based automated approach and the application of engineering ontologies. EG-ICE 2014, European Group for Intelligent Computing in Engineering - 21st International Workshop: Intelligent Computing in Engineering 2014, 2014.

Chapter 1 Introduction

1.1 Background

The impact of construction sector on sustainability has been persistently discussed and well documented (Spence and Mulligan, 1995, Hill and Bowen, 1997, Pearce, 2006, Kibert, 2007, Michael et al., 2009). The construction industry contributes significantly to society and economy in most countries of the world (Burgan and Sansom, 2006). In the UK, it accounts for around 10% of gross domestic product (GDP) (UK Department of Trade and Industry 2007). In terms of the environmental impact, the construction sector is one of the largest consumers of natural resources as well as producers of waste and pollutions. For example, in the UK, building environment accounts for 50% of the nation’s energy consumption and 47% of CO_2 emission (Edwards, 1996, Smith et al., 1998). Governments and institutions are engaged in implementing strategies to reduce energy consumption and greenhouse gas (GHG) emission. The UK government has set the 2050 emission target that commits to cut greenhouse gas emissions by 80% from 1990 levels by the middle of this century (Ekins et al., 2012). The building construction sector has been identified to play a key role in this commitment. Therefore, the concept of sustainable design has become an ethical standard and a goal for the industry (Ochsendorf, 2005).

Although structural engineers have not played a leading role in the shift of traditional design to sustainable design, the attempt to define the proper role for the structural engineer in the pursuit of sustainability of built environment has never stopped (Krem et al., 2013). In 2014, the IStructE (The Institution of Structural Engineers, 2014) published a guide to assist structural engineers in delivering sustainable projects. Over the last decade, the energy consumption and carbon emission due to large production and usage of building material, known as embodied energy and carbon, have become a major concern that structural engineers are directly responsible for. 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 (Huovila et al., 2007). Therefore, it is imperative for structural engineers to provide more sustainable structural design to mitigate the environmental impact. The effective building design requires smart and holistic tools that can process multi-objective and inter-connected domain knowledge to provide genuine sustainable buildings.

The information and communication technologies (ICT) have promoted the evolution of information and knowledge management in construction industry. In particular, the applications of building information modelling (BIM) and Semantic Web technology expedite the transition of knowledge management paradigms in AEC industry - from document based human interpretation to semantic based system (ontology) (Rezgui et al., 2010). In recent years, ontologies have been applied to a wide range of domains in construction sector; for example, construction project management, smart home and sustainability appraisal. This research focuses on the use of Semantic Web technology in the integrated system development for sustainable structural design.

1.2 Motivation

Because of the large amount of construction materials used in structures (especially in the tall buildings), the importance of structural engineering in sustainable building design has been increasingly recognised (Borchers, 2010). Design decisions taken by structural engineers could make significant contributions to the reduction of environmental impact caused by construction without compromising the economic benefits. To achieve the maximum influence on building cost and impacts in building life cycle, it is widely acknowledged that the design stage presents the best opportunity to incorporate sustainability measures into the project development process (Ding, 2008, Kohler and Moffatt, 2003, Todd et al., 2001). However, opportunities are often missed because of a number of barriers. Firstly, the contribution of structural engineers to sustainability is limited due to the major attention paid to the reduction of operational energy in building maintenance stage. Secondly, there is a plethora of construction sustainability information fragmented and located in a distributed way in various locations using different formats. This makes it difficult and sometimes impossible for structural engineers to make informed decision on sustainability. Thirdly, structural engineers have insufficient tools on quantifying the environmental impact of building structure and evaluating the sustainability of design solutions at early stages. Existing sustainability assessment tools focus heavily on completed buildings rather than the design phase. In terms of structural design, according to an evaluation from Miller (2015), the UK's Building Research Establishment's Environmental Assessment Method, the USA's Leadership in Energy and Environmental Design and the Green Star rating system developed by the Green Building Council of Australia all enable the designing structural engineer to influence only between 7% and 11% of the points attainable under these systems. Furthermore, current practice of structural design lacks the ability to suggest alternative design solutions with potential sustainability benefits. Under these circumstances, there is a need to apply advanced information and communication technologies (ICT) to manage and incorporate sustainability knowledge into the structural design process. By doing so, the contributions to curbing greenhouse gas (GHG) and energy consumption are more pronounced from the structural engineers' perspective.

Existing research findings suggest that modelling of disparate knowledge on different domains requires a rich semantics based language that can be read not only by human but machines (Fensel, 2003, Alesso and Smith, 2006). The Semantic Web has emerged as a powerful platform that allows structured contents to be automatically processed by computer. Ontology as one of the Semantic Web technologies have been applied intensively for knowledge modelling, developing, sharing and utilising in a wide range of domains, such as agriculture (Goumopoulos et al., 2009), bioinformatics (Bard and Rhee, 2004), economy (Yoo and No, 2014), and medicine (Rosse and Mejino Jr, 2003). Semantic Web technologies are ideal for modelling complex systems in the construction sector. In contrast to static terminology structures used for knowledge reference, semantic ontologies allow us to describe concepts at the taxonomy level and sophisticated relationships between the concepts (subsumption, cardinality, jointness, etc.), thus allowing for knowledge inference and reasoning (Osman et al., 2015). Considerable amount of studies has attempted to incorporate ontologies in construction domain for various applications. One of the most notable applications is construction information and knowledge management. A wide range of endeavours, from establishing taxonomy across disciplines to particular domain conceptualisation, has been investigated to facilitate the knowledge management practice in construction industry. These efforts, together with the rapid development of Building Information Modelling (BIM), trigger an evolutionary shift of knowledge management paradigms, from human interpretable knowledge systems to semantic based automatic knowledge systems around the use of ontology (Rezgui et al., 2010).

In summary, the motivation of this study stems from the following four aspects: (1) the importance of sustainability in construction sector; (2) limitation of existing sustainable development in structural design; (3) advances of BIM and Semantic Web technology and (4) paradigm shift of knowledge management in the AEC domain. The core features of ontology, inclusive of semantic structure, machine processing capability and reasoning function, provide an important opportunity to overcome the shortcomings of current sustainable structural design practice and facilitate the development of computer aided decision support system.

1.3 Problem statement

Based on the literature review of current practice of sustainable structural design, a number of research gaps have been identified:

1. The knowledge and information of sustainable development for building structural design are generally fragmented;
2. Tools dedicated to inform design-decisions based on evaluating sustainability of design solutions are generally lacking for the structural engineers;
3. In addition to the issues associated with quantifying sustainability in the built environment, current sustainability assessments are based on completed building, it to some extend compromises the usefulness of sustainability rating in design decision

making stage. However, the best opportunity to improve the sustainability performance of a building is at early design stage.

4. Current commercial available sustainability ratings systems play limited role in decisions-making process of structural design due to the lack of quantitative terms for qualifying sustainability;

5. Sustainability issues should be considered together with other structural design criteria holistically. However, they are dealt with in a separate stage in conventional practice, where the sustainability assessment such as calculating the amount of embodied energy is normally carried out after the completion of structural design and analysis.

6. More importantly, limited design options are provided in current structural design practice, even simply copying from previous projects, which loses the opportunity to compare with design alternatives that potentially gain more sustainable benefits.

In summary, the problem statement is concluded as follow: ***In conventional structural design practice, the structural engineers are limited in sustainable development due to a lack of efficient computer-aided tools for managing fragmented knowledge and information associated with sustainability in structural design, qualifying the design solution with quantitative terms, holistically considering multiple criteria and providing design options with potential sustainable benefits at early stage.***

Therefore, this research seeks to solve the above problem by answering the research question: ***how ontology and other Semantic Web techniques can be used to model sustainability related knowledge for decision support at structural design stage?***

1.4 Research hypothesis and questions

Following the problem statement, a research hypothesis has been devised as below:

With the use of ontology, the multi-domain sustainability related knowledge can be created and integrated to form a holistic knowledge base, which can be further leveraged by rule-based reasoning to provide smart decision support regarding sustainability for structural design.

Having proposed the hypothesis, question arises of how to support it. A group of questions is concluded below and the answers to them correspond to different chapters presented in this thesis:

1. What are those related domains that structural engineer should and can consider for sustainable requirements? (Chapter 2)

2. How to create a holistic knowledge base that merge structural design, embodied energy, CO_2 emission, cost, supplier selection and so on together? How to create relevant holistic rules to address potential sustainable design questions raised by structural engineers? (Chapter 3 and 5)

3. How to implement an ontology based design tool that can provide real time query results using Semantic Web rule language for structural engineer to consider sustainability requirements? (Chapter 4)

4. How to develop and validate the proposed ontology? (Chapter 5)

5. How to validate the developed system? (Chapter 6)

1.5 Research objectives

The overall aim of the study is to investigate how Semantic Web technologies can be used to manage domain knowledge on sustainability and structural design, and to develop a prototypical system to assist structural engineers in decision-making process by choosing appropriate sustainable structural design solution at early design stage. To achieve the overall aim and answer the questions listed above, the research objectives have been set as follows:

1. Identify domain knowledge and methodology of sustainable structural design;
2. Identify the gaps in current practice in managing sustainable building structure knowledge;
3. Explore the Semantic Web technologies and how to use the technologies to bridge the gaps;
4. Establish a knowledge model capturing sustainable structural design information and knowledge using ontology and rules;
5. Implement a sustainable design decision-support prototype system based on knowledge model;
6. Validate the prototype system using typical structural design case to demonstrate the validity of the system and potential of Semantic Web applications in AEC domain.

1.6 Summary of research methodology

The underpinning research methodology adopted in this study is exploratory study and prototype system development with case study evaluation. The implementation of exploratory study is to provide primary insight into the problem domain. Based on the findings from exploratory study, the research hypothesis and subsequent research methods and activities can be determined. Prototype system is developed to support the proposed hypothesis. Figure 1.1 shows a simplified framework of the adopted research methodology.

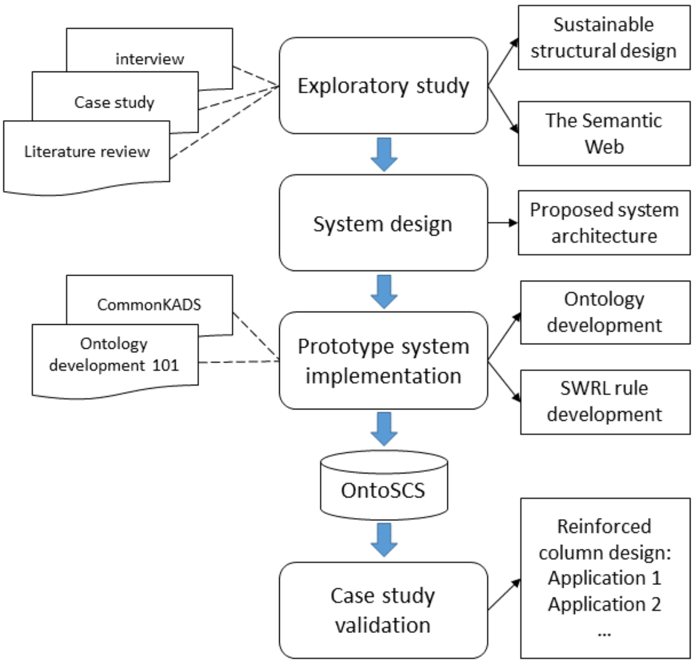


Figure 1.1 Simplified framework of research methodology.

The exploratory study consists of two targeting domains: sustainable structural design and the Semantic Web technology. The sustainable structural design domain is the first focus area where the understanding of technologies and principles of this domain are established. In addition, the identification of the research gaps in the problem domain has led to the conclusion that a decision-support tool is necessary for sustainable structural design. Considering the large scale of building structure domain, it is more intuitive and practical to focus on a specific structure. This is the reason that concrete structure design is chosen to demonstrate the proposed system. The insight of the knowledge related to the sustainability and structural design domains motivates the investigation of the Semantic Web technologies. Similar as the exploratory study conducted in sustainable structural design domain, literature review, workshops, interview, and case study are the main techniques used for establishment of state-of-the-art in the Semantic Web domain. The main outcomes include: Firstly, the review of current Semantic Web technologies and applications in construction sector justify the feasibility of using them for developing a knowledge-based integrated system in sustainable structural design domain. Secondly, the specific Semantic Web technologies, OWL ontology and SWRL rules are identified for the use of modelling sustainable structural design knowledge. Furthermore, based on the choice of technologies used in this study, the corresponding knowledge engineering and ontology engineering methodologies are determined consequently. CommonKADS and Ontology Development 101 are the main methodologies to develop the ontology-based knowledge model in this study. To validate the knowledge model, a prototype system named OntoSCS (Ontology-based Sustainable Concrete Structural design) has been developed in the Protégé-OWL environment. A real-world case, reinforced concrete column is designed to evaluate whether the prototype system works as intended.

1.7 Main contributions

The motivation of the work presented in this thesis is the demand of new generation knowledge oriented decision-support tool for multi-objective building/structure design considering sustainability. The Semantic Web technology can be used as knowledge representation technique for this demand. Therefore, the study is established on thorough literature review of appropriate techniques, tools and methodologies of the Semantic Web, and development of a prototype system using selected Semantic Web technologies for sustainable structural design. The main contributions have been concluded below:

1. Proposed and realised an innovative ontology based holistic decision making framework, which can be utilised by structural engineer to design more sustainable structures with systematic consideration for structure feasibility, durability, safety, embodied energy, CO_2 emission, cost, supplier selection, and sustainability assessment.
2. Identified relevant knowledge about sustainability in building structural design;
3. Created a unique formal OWL ontology to represent knowledge in structural design regulation and associated sustainability information by managing interconnected relationships of multiple domains.
4. Established an approach applying SWRL rules to represent structural design criteria and taking advantage of reasoning function to conduct structural design calculation;
5. Adopted Semantic Web queries to achieve multi-criteria selection in sustainable structural design;
6. Implemented a research prototype system named OntoSCS, which demonstrates the use of the developed ontology model in practical concrete structure design.

1.8 Research scope

The research is inter-disciplinary oriented, concerning two major domains, e.g. sustainable structural design and the Semantic Web. Each of the two domains is vast. Therefore, it is important to specify the scope of this research in terms of key aspects, e.g. building life cycle stage, sustainability dimension, architecture of information system, and implementation level.

1.8.1 Building life cycle stage

The building life cycle is a process combining design, construction, operation, maintenance and demolition. The early design stage provides the best opportunity to improve sustainability without compromising economic benefit. Therefore, this study focuses on structural design stage. The proposed decision-support system could maximise the usefulness by informing structural engineers the optimised design alternatives at structural component design stage.

1.8.2 Sustainability dimension

The commonly considered sustainability consists of three aspects: environmental, social and economic issues (Atkinson, 2008). However, this study mainly deals with the environmental and economic aspects. It is because methodology of accounting for the social aspect of sustainability is not fully developed (Kloepffer, 2008). Although the design of building greatly affects the way people love and work, there are still inadequate indicators that are able to accurately measure the social impact of buildings. Additionally, the impact of social factor on structural design is relatively small, because the social aspects of a construction project have been envisaged by client and designer at conceptual stage before structural engineers engage. Due to these reasons, this study proposed a holistic approach that integrates a group of sustainability factors, including structural feasibility, embodied energy and carbon, durability, fire safety and cost to evaluate structural design options.

1.8.3 ICT system architecture

The N-tier architecture is a widely adopted system framework divided into several tiers: Client or web browser, the presentation tier, the application logic tier and database tier (Alonso, 2004). In this study, only application logic tier and database tier will be developed. The choice is based on the consideration that different presentation layers should be designed to meet various requirements of end-users. It is possible to develop application interfaces involving client and presentation tier as front-ends in future work, which has been discussed in Chapter 8.

1.8.4 Implementation level

Due to the limited resource and time of PhD research, a prototype rather than mature system is implemented for proof of concept and evaluation. Developing a research prototype is an appropriate approach for emerging technology applications that require rapid and flexible response to changes and continuous improvement.

1.9 Thesis structure

The thesis consists of eight chapters. The content of each chapter is briefly introduced.

Chapter 1 establishes the fundamental of this thesis by stating the background, motivations, hypothesis, objectives, contributions and scope of the research.

Chapter 2 undertakes an exploratory study to review sustainability in building structural design, integrated system and the Semantic Web technologies. The rapid development of ICT facilitates the sustainable development in AEC/FM industry. Different system integration approaches such as software agent and Web service are introduced as well. The Semantic Web has been selected to develop the holistic system for integration of sustainability and structural design. Key concepts such as the Semantic Web architecture, Ontology, and Semantic Web Rule Language (SWRL) are introduced respectively.

In Chapter 3, key methodologies for developing prototype have been reviewed. Based on the review, CommonKADS and Ontology Development 101 have been chosen as the knowledge engineering methodology and ontology engineering methodology respectively. This choice leads to the selection of ontology and rule language, and development tools.

Chapter 4 presents the architecture of prototype system named OntoSCS. The requirements of developing an ontology-based knowledge system are discussed. A prototype system is proposed to meet the requirements, consisting of three core parts: knowledge base, ontology management system and inference rule engine respectively. In addition, system components of the software environment are introduced.

Chapter 5 demonstrates the procedure of establishing OntoSCS system in Protégé software. Key steps for ontology and rule development are explained following the methodology chosen in Chapter 4. The adoption of manual and automatic validation approaches ensures the semantic and syntactic correctness of developed ontology.

Chapter 6 deals with the validation of the completed prototype. After the technical evaluation, a real-world design case is used to validate the function of prototype system. Different design scenarios with multiple sustainable requirements are presented to demonstrate the system’s capability: retrieving information and using a multi-criteria based holistic approach to select appropriate structural design alternative considering different aspects of sustainability. The results from the case study will support the hypothesis of this research.

Chapter 7 concludes the achievements of this study and contributions to the current knowledge. In addition, the limitations of this study are discussed.

Chapter 8 discusses how to extend the scale of the system proposed in this thesis and explores the possibility of integration with external information system.

Chapter 2 Literature Review

This chapter presents a literature review in four sections. Section 2.1 begins with identifying the importance of sustainability in modern human society. Construction industry has been recognised as a key sector for sustainable development due to the vast consumption of natural resource. Structural engineers play a critical role in designing sustainable building by reducing the energy consumption and greenhouse gas (GHG) emission associated with structural materials, specifically the embodied energy and carbon. The findings and gaps identified based on the critical analysis of the review explains the motivation of this study, which raises the demand of developing a knowledge-based integrated system for sustainable structural design. Section 2.2 introduces system integration technologies in the AEC/FM industry. Interoperability between different information system is discussed followed by the review of different system integration standards and approaches. The Semantic Web approach is selected for information integration and knowledge management in this thesis. Therefore, the background knowledge of Semantic Web technologies is explored in Section 2.3. As an exploratory study, this section has been categorised into four main parts. The first part reviews the limitations of current web and the essential motivations behind the development of Semantic Web technology. The second part introduces the architecture of Semantic Web and key components. The third part investigates the concept of ontology and Web Ontology Language (OWL), also deals with query language for Semantic Web. The last part provides an overview of important developments of Semantic Web applications in building construction domain, following a critical analysis of the review. Finally, the knowledge management paradigm in construction sector is discussed in Section 2.4, which supports the rationale of using the Semantic Web approach in this research.

2.1 Sustainability in built environment

2.1.1 The broad nature of sustainability

Over the last three decades, sustainability has become increasingly important (Miller and Doh, 2015). Nowadays, sustainability is a worldwide concern due to the pressures from global population growth and climate change. It is important to distinguish between sustainability and sustainable development. Sustainability is regarded as the destination or aim, while the sustainable development is the process to achieve this aim (Georgopoulos, 2014). In 1987, the United Nation released the Brundtland report “Our Common Future”, in which the sustainable development is defined as “development which meets the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment Development, 1987). Spence and Mulligan (1995) corroborated this global interpretation by explaining the relationship between human and the world. They mentioned that there was a need of combining two goals for sustainable development, eliminating the inequities between counties to accelerate the human development globally; while at the same time preventing the planet from depletion of resources and biological systems to ensure future generations will not be impoverished.

Global efforts have been made to the sustainable development especially over the last two decades. For instance, the Kyoto Protocol (O'Neill and Oppenheimer, 2002) negotiated in

December 1997 and the 2009 Copenhagen Accord on reducing of the emissions of greenhouse gas (GHG) to tackle climate change issues (Ramanathan and Xu, 2010). Furthermore, these efforts led to more progressive achievements on sustainable development, such as the international treaty on reducing the global warming - the United Nations Framework Convention on Climate Change (UNFCCC, 2010), which is ratified by most countries in the world.

In terms of the domestic efforts, the UK sustainable development goal states that (DEFRA, 2004) “the goal is to enable all people throughout the world to satisfy their basic needs and enjoy a better quality of life, without compromising the quality of life of future generations”. This is not different in interpretation from global view and it aims at living a quality life today without ultimately jeopardising the well-being of future generations. A number of promotional activities has been initiated and pushed forward through departments of UK government. Accordingly, a series of reports has been published such as “Sustainable development indicators in your pocket” covering a wide range of initiatives, goals and actions by the government. The UK government pointed out four key elements for sustainable development strategy (HM Government, 1999): social progress recognising the needs of every one; effective protection of the environment; prudent use of natural resources; and maintenance of high and stable levels of economic growth and employment. In summary, sustainability is now commonly recognised as a combination of “triple bottom line” balance of environmental, social and economic issues as shown in Figure 2.1 (The Institution of Structural Engineers, 2014). The only way to reach sustainability is each of three aspects is appropriately considered for any given product, service or process (Lélé, 1991, Spreckley, 1983).

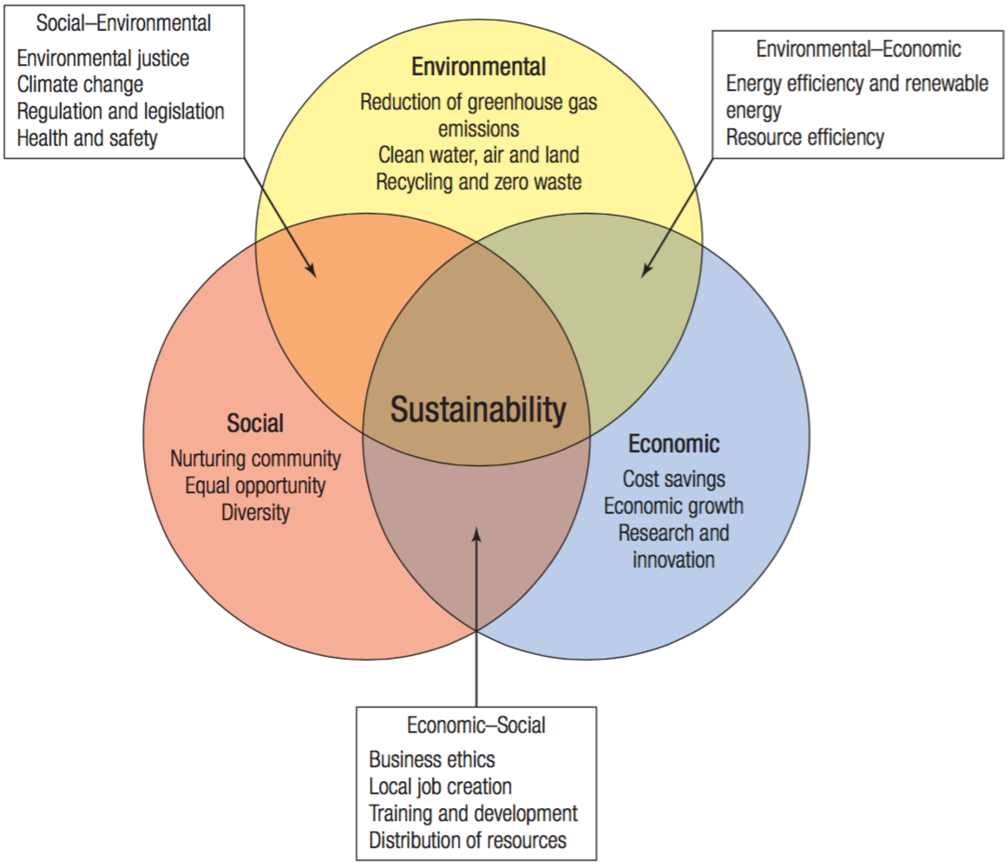


Figure 2.1 The triple bottom line of sustainability (The Institution of Structural Engineers 2014).

2.1.2 Sustainability in building construction

The pressure on and requirement for the adoption of sustainable development have led to the construction industry being identified as one of the key sectors with significant impact on sustainability (Miller et al., 2015) because of the high economic significance, strong social effect and environmental impacts (Burgan and Sansom, 2006, McCarthy et al., 2008).

2.1.2.1 Economic aspect

The building industry is referred to as the lifeblood of the economy in the world (Miller et al., 2011). Its contribution to the economic dimension of sustainable development is unquestioned, representing 2-3% of GDP in developing countries and accounts for over 50% of national capital investment in most countries. Additionally, the construction industry contributes around 7% of world employment with over 100 million workforce worldwide (UNEP, 2003). In developed areas and countries such as Europe and the US, construction is the largest industrial sector contributing 10-11% and 12% respectively of GDP in these two continents (UNEP, 2003). In the USA, the construction industry is valued at over $1 trillion and provides critical infrastructure to support industries while creating over 6.5 million jobs (Chong et al., 2009). In Europe, this industry provides the largest single contribution to employment with over 7.5%, 9.7% of the GDP and 47.6% of the gross fixed capital formation respectively (European Union, 2001). And now these trends continue globally. In terms of the UK, the Egan Report noted that the construction industry was responsible for 10% GDP and 1.4 million employment (Egan, 1998).

2.1.2.2 Social aspect

The social benefits provided by structurally sound buildings are also extensive (Miller et al., 2015). They provide good quality indoor living environments, delivering a significant degree of structural integrity, low vibration, excellent weather protection, high fire resistance, good thermal resistance and sound acoustic performance.

2.1.2.3 Environmental aspect

On the contrary, the construction industry has made negative impact on environment. It has been recognised as the largest single anthropogenic contributor to environmental pollution and climate change due to the massive consumption of natural resource, land use and material extraction (Yeo and Gabbai, 2011). The construction, operation and maintenance of buildings account approximately 40-50% of global energy usage and anthropogenic greenhouse gas

(GHG) emissions (Hasegawa et al., 2003, Smith, 2001, Asif et al., 2007, Citherlet and Defaux, 2007, Baek et al., 2013). In the US, construction industry consumes over 40% raw material and energy annually (Chong et al., 2009). In the UK, buildings account approximate 50% of the total commercial energy consumption of the country, while releasing around 300 million tonnes of CO_2 each year, which take up to around 50% of total CO_2 emissions of the country according to the estimates from Edwards (1996) and Smith et al. (1998). Consequently, the enormous consumption of natural resource results in negative impacts on environment, producing large amount of pollution to the environment. Furthermore, the construction sector is connected to every environmental crisis experienced in the world such as water shortage, global warming, and energy crisis, since it interlinked closely with energy, resource and environment (Swamy, 2001).

2.1.2.4 Sustainability assessment

In recent times, mechanisms have been developed globally to reduce environmental impact by improving environmental performance of buildings. One of the most notable progresses is to extensively develop rating standards and systems aiming to quantify the sustainability attributes of buildings (Goh and Rowlinson, 2014). The Building Research Establishment Environmental Assessment Method (BREEAM) is regarded as the first “comprehensive means of simultaneously assessing a broad range of environmental considerations in buildings” (Crawley and Aho, 1999). It was established as the first commercial environmental assessment tool for buildings in 1990 in the UK (Grace, 2000). Since then, a variety of sustainability assessment systems has been developed and implemented in worldwide construction projects over last decades, many of which have gain considerable success (Lee, 2013, Haapio and Viitaniemi, 2008, Goh and Rowlinson, 2014, Alyami and Rezgui, 2012). A summary of existing sustainability assessment system in construction sector is shown in Table 2.1.

Although most of these assessment systems cover economic, social and environmental sustainability of a project, the degree of measurement on these aspects still varies greatly. In different targeted construction projects, various sustainability assessment systems have placed the emphasis on different aspects. However, the mechanisms of most assessment system are quite similar. These systems consist of a group of prescribed qualitative and quantitative criteria focusing on various aspects of sustainable development. The benchmark of each project performance is subsequently obtained from accumulating all the criteria achieved and then balanced in a design weight system (Goh and Rowlinson, 2014).

Table 2.1 Summary of existing sustainability assessment system in construction sector.

Regions	***Sustainability assessment systems***
UK	Building Research Establishment's Environmental Assessment Method (BREEAM)
US	Leadership in Energy and Environmental Design (LEED); Green Globes; DOE's Energy Star; ASHRAE Green Guide
Europe	Eco-labeling
The Netherlands	GreenCalc
Canada	Canada's Green Globes (GBI); Sustainable Building Tool (SBTool)
China	China's Green Olympic Building Assessment System (GOBAS); LEED; Three Star
Australia	Green Star; Australia's Building Greenhouse Rating (ABGR)
Japan	Comprehensive Assessment System for Building Environmental Efficiency (CASBEE 2006)
Korea	Green Building Rating System (GBRS)
Hong Kong	Building Environmental Assessment Method (BEAM Plus); LEED
Singapore	Green Mark
India	TERI-GRIHA

The importance of reducing the environmental impact of buildings and infrastructure project has been agreed. To achieve this target, it is imperative to facilitate the sustainable development in construction industry, and change the way of design and build (HM Government, 2008). The building project involves a group of activities from design to completion and maintenance, where the design has been identified as a critical stage to improve sustainability of building. As illustrated in Figure 2.2, there are more opportunities of improving the sustainability of a building project without costing too much in the early design stage than construction stage or operation stage (The Institution of Structural Engineers, 2014).

The holistic design (or integrated design) process is crucial in producing a sustainable building (Lewis, 2004), with considering all factors that affect the sustainable performance and provides optimised solutions. For example, the structural engineers should make decisions not only according to the structural performance, but also consider the environmental impact, durability and economic benefit in holistic design workflow.

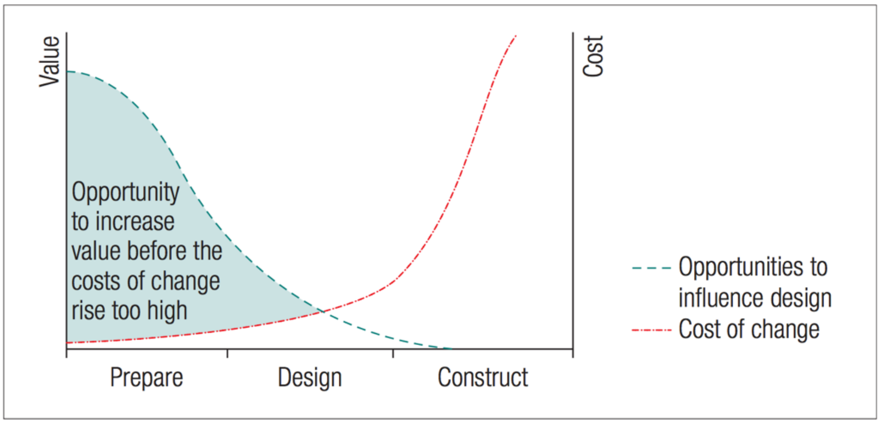


Figure 2.2 Value and cost of implementing sustainable decisions changes throughout project stages.

2.1.3 Sustainable structural design

In traditional design workflow, structural engineers play a distinguished role in the building design team with primary focus on the structural integrity. However, in fact, there has been a wide range of impacts on the environment that structural engineers are directly or indirectly able to influence, from the depletion of non-renewable resources and the adverse impacts of manufacturing and construction processes on the climate, to the structure's impact on climate change, air and water quality, and its local environment (The Institution of Structural Engineers, 2014). In addition, the inefficient design of buildings and their associated infrastructure becomes the direct reason that results in the dispensable consumption of resource (Paya-Zaforteza et al., 2009).

2.1.3.1 Structural engineer's role in sustainable development

Over last decade, the structural engineering profession has been attempting to define the proper role for the structural engineer in the pursuit of sustainability in built environment (Krem et al., 2013). Webster (2004) and Anderson and Silman (2009) identified the role of the structural engineer in an integrated design team of architects, engineers, builders, and owners to make the structure sustainable. The American Society of Civil Engineers (ASCE) has recently published "Sustainability Guidelines for the Structural Engineer" (Kestner et al., 2010), providing guidance to reduce environmental impacts for all common material types. The Institution of Structural Engineers in the UK published a series of guides to assist structural engineers in the delivery of sustainable projects, with discussion of elements that are critical to overall sustainable design such as energy, planning, transport, and water (The Institution of Structural Engineers, 2014, The Institution of Structural Engineers, 2011). Therefore, the structural engineers should incorporate sustainable development principles into design process with consideration of all three dimensions of the “triple bottom line”, gaining economic and social benefits while concurrently minimising related environmental impacts.

Generally, reducing energy and carbon emission associated with materials employed in structural components are the main targets for structural engineers to focus on to improve sustainability. The total energy consumption and carbon emission in modern building could be classified in two catalogues: embodied and operational (Goggins et al., 2010, Dixit et al., 2010, Dixit et al., 2012, Dixit et al., 2013), as shown in Figure 2.3.

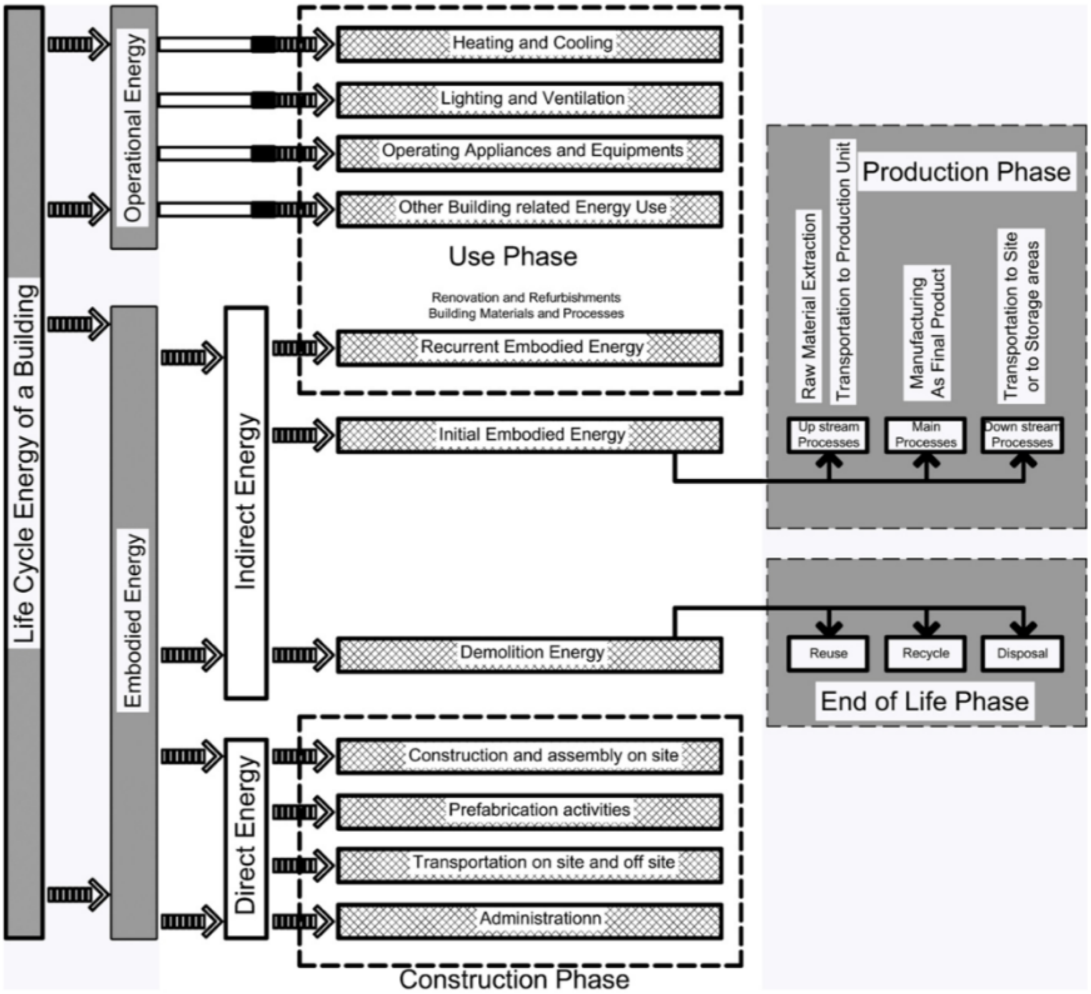


Figure 2.3 Embodied energy and operational energy modelling (Dixit et al. 2012).

In the current building design process, structural engineer plays a limited role in the overall sustainability of a design (Paya-Zaforteza et al., 2009). One of the main reasons is because most of energy required by buildings is consumed in operation stage to run and maintain the building. According to a case study of new-building housing in UK by Iddon and Firth (2013), the operational emission represents 74% - 80% of total amount emission of a house in 60 years; while the embodied emission represents 20% - 26%. Thus, the majority of efforts to improve sustainability of buildings focuses on reducing the operational energy (Ibn-Mohammed et al., 2013), which is beyond the scope of a structural engineers' influence (Ramesh et al., 2010, Crawford, 2011). Additionally, it is not practical for a designer using operational energy to predict the effect of structural design decision on environmental performance (Adalberth, 1997, Mithraratne and Vale, 2004). Although the focus of building regulations in the UK has been on operational energy and carbon emission, the situation has been changing with many studies presenting the importance of considering embodied energy for design decisions (Thormark, 2006, Sartori and Hestnes, 2007, Dimoudi and Tompa, 2008, Baek et al., 2013). Because zero carbon buildings are promoted in UK for residential in 2016 and for other buildings in 2019 (HM Government, 2011), then the vast majority of whole life cycle energy consumption and carbon emission are embodied in the building materials. In the UK, this part is estimated to account for 10% of national energy consumption (Huovila et al., 2007, Ibn-Mohammed et al., 2013). In terms of single building, a study of 60 cases in nine countries by Sartori and Hestnes (2007) found a large variation of the percentage of embodied energy's share in total energy consumption, from 5% up to 40%. Because of the increased awareness across construction sector to their impacts, embodied energy and carbon have been widely accepted as appropriate indicators to measure the environmental aspect of building sustainability (Alcorn and Baird, 1996, Cole, 1999, Dixit et al., 2010, Cabeza et al., 2013, Aye et al., 2012).

2.1.3.2 Embodied energy and carbon in structural materials

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 (Hammond and Jones, 2008, Venkatarama Reddy and Jagadish, 2003). Most values adopted in this research are taken from the ICE (Inventory of Carbon & Energy) database, which is developed by Hammond and Jones from University of Bath. This inventory is a reliable and open-access database providing over 400 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. 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 that captures more than just carbon dioxide.

2.1.3.3 Approaches of sustainable structural design

A number of methods can be adopted to reduce embodied energy and carbon in building structures, such as using green material, optimising structural element size and selecting certificated material suppliers. From a practical point of view, there are various methods to design a structural element or system to meet the needs of the owner and user while minimising the environmental impact (Danatzko and Sezen, 2011).

- Firstly, minimising material use is essential to reduce the amount of required raw materials, and in turn, reduce the project’s impact on the environment. More specifically, this goal can be achieved by using combination of various type of materials or optimising structural members (Shi and Han, 2010).

- Minimising the embodied energy is the second method that can be achieved by structural engineers. This method aims to reduce the amount of energy consumed for the construction material production, which requires structural engineer to specify the sustainable property of structural material in addition to the structural properties, and employ energy-efficient product in design.

- The third method is minimising the energy associated with construction stage. The concept behind this method is effort by structural engineer to consider the energy cost of construction activities, such as transport of materials.

- Other methods include adopting sustainability assessment, reuse of structural components or materials, and choosing responsible source for material. For instance, British Standard Institution (2008) published BES 6001 to provide a framework to benchmark construction product based on the way of raw material mining, processing and manufacturing. The certificated material suppliers are available on greenbooklive.com for designer to select.

In recent years, there has been an increasing amount of study aiming to reduce 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.

A study (Kaethner and Burridge, 2012) undertaken by Arup and The Concrete Centre 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 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. There is greater potential to minimise the embodied carbon by careful design and specification of concrete components in buildings than choice of structural form. 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. (2014) discussed the cradle-to-gate embodied energy of high building structures in the newly published paper. A reinforced concrete central core with 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, and four lightweight floor systems: (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. (2011, 2015) 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.

2.1.3.4 Findings from the review of sustainable structural design

By critical analysing the knowledge and existing work related to sustainable structural design, this section outlines some key findings form the review, also identifies some gaps in current sustainable development for structural design practice.

Findings from the review:

1. The energy used for extraction, production and transport of structural materials such as cement, concrete, steel and wood accounts large share of lifecycle energy consumption of buildings. The energy consumed in this phase is categorised as embodied energy. With the promotion of Net-Zero Energy Building (ZEB) (Marszal et al., 2011), the impact of embodied energy to sustainability of buildings becomes even more significant (Yeo and Gabbai, 2011).

2. Building construction sector is energy intensive, accounting 50% of domestic energy usage and releasing around 300 million tonnes of CO_2 each year. Identification and development of indicators are one of the main areas of research in sustainable building design. To measure the environmental impact caused by building structure, the embodied energy and embodied carbon have been proved as appropriated indicators. Most research related to sustainable structural design have been using embodied energy and carbon to evaluate the sustainability of structures (Yeo and Potra, 2015, Oti and Tizani, 2015). Moreover, the professional institute of structural engineering recommend considering embodied energy and carbon in sustainable structural design (The Concrete Centre, 2014).

3. The role that structural design plays in sustainable development of building construction project is to reduce the embodied energy and carbon emission associated with structural materials including concrete (Anderson and Silman, 2009, Miller and Doh, 2015).

4. The design stage offers the best opportunity to improve the sustainability of buildings with minimum cost and effort. Therefore, it is important to incorporate consideration

of sustainable issues in early design stage. This requirement creates demand on adopting various measures and techniques to assist structural engineers in reducing environmental impact of their design solutions.

5. From structural engineers' perspective, there are mainly three ways of reducing embodied energy and carbon in design stage (Hou et al., 2015). Firstly, novel building materials with less embodied energy and carbon, such as low-carbon cement become a priority of material selection. Secondly, the reduction can be achieved through optimisation of structural design. Additionally, improving supply chain of construction materials and selecting nearby suppliers would decrease the embodied energy and carbon generated by transport.

6. Material specification plays more important role than choice of structural form in reducing environmental impact. In general, concrete structures perform better than steel structure in sustainable aspect (Kaethner and Burridge, 2012).

7. Since concrete is the most widely used structural material in construction project, there is large amount of embodied energy in concrete structure (Portland cement production contributes 5% of global CO_2 emissions and 3.8% of global energy use) (Hooton and Bickley, 2014). For this reason, the focus of this study is on sustainable design of concrete structure. However, the principle and methods for sustainable structural design are nonetheless applicable for other structural form such as steel structure.

Gaps in current sustainable structural design:

1. The importance of reducing embodied energy and carbon through structural design is not widely understood. Most efforts of sustainable development in construction sector focuses on reducing energy consumption in operational stage.

2. In terms of current commercial available sustainability assessment tools, there are three shortcomings of their use for structural design. Firstly, most of current sustainability assessment tools focus on completed buildings instead of building in design stage. Secondly, evaluation of building sustainability is often conducted in the relatively late stage that loses the best opportunity to incorporate changes. Thirdly, existing assessment systems only allow structural engineers to make limited influence (around 7%) to the attainable points that related to the use of material issue (Miller and Doh, 2015). Therefore, at the early design stage, the structural engineers are limited to make positive impact on sustainability due to the absence of decision-support tool that could quantitatively specify the impact associated with structural element.

3. Owing to the fragmented nature of construction industry (multiple disciplines, various software/ tools, and different phases), the knowledge and information about sustainable structural design is complex and often difficult to access. Information related to structural sustainability is distributed in various formats and locations, for instance, paper guidance, databases and web pages. Considering sustainable issues in conventional structural design practice is time-consuming, which requires lots of effort to retrieval useful information.

The shortcomings could be overcome by developing an efficient knowledge management tool for structural engineers. From a practical point of view, an integrated system could manage distributed sustainability information with structural design knowledge. 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 specify material selection and optimise structural dimension, minimising the whole life cycle energy consumption and carbon emissions. Therefore, the development of integrated system is the core of this research. In the next section, system integration approaches in building construction domain will be explored.

2.2 System integration in construction industry

The AEC/FM industry is fragmented due to the complex but close interrelated nature of building project, which requires the involvement of multidisciplinary teams (including owners, architects, consultants, engineers, contractors, sub-contractors, and suppliers), and the use of heterogeneous software and hardware systems/tools in different phases of project life cycle. Information plays a key role in these interactions between disciplines. Dawood and Sikka (2009) highlights the importance of information as “construction industry is information-based by nature”. Therefore, the development of holistic and integrated system becomes an important prerequisite for effective and efficient information sharing and exchange. With the advancement of information and communication technology during the past 15 years, various system integration approaches have been developed and implemented to different applications. This section illustrates system integration technologies in the AEC/FM industry based on a review by Shen et al. (2010).

2.2.1 Interoperability

The fundamental idea of system integration is enabling two or more systems to communicate, share and exchange information, and to inter-operate to achieve a common objective. Interoperability, the ability that data generated by one party can be interpreted by all other parties, is the first and most important step towards system integration. In ICT domain, the data interoperability is achieved from data modelling. A data model organises the data of a domain of interest in a manageable manner, containing all the definitions of objects, constraints and relationships between objects in the domain.

Taking construction domain as an example, it typically involves various software/tools from different vendors to conduct specific task by different disciplines; for instance, architectural design, structural analysis, construction management and operation control. To share information/data among the parties in such a heterogeneous environment, the demand of a common data model has increased. With a common data model, all parties are able to generate and interpret the data in a same manner, and all information related to building project is able to be created, integrated, managed and enriched throughout the project’s life cycle. This reduces the risk of errors and inconsistencies caused by recreating data during information exchange.

Apart from data interoperability, framework interoperability is also important to system integration. Data interoperability focuses on developing common data models, while framework interoperability is achieved by common communication language and protocols. For example, the communication of two different sensors depends on not only common data format but also common protocol and language. The data interoperability is preferable in centralised integration approach. On the other hand, in a distributed integration approach, the framework interoperability is more important. It allows different systems to solve each own problem using different data models while still be able to work together through common languages and protocol.

2.2.2 Standards for interoperability in construction industry

Over the last 20 years, the AEC/FM industry has been developing a number of international and industry standards to address the interoperability issues.

2.2.2.1 The Industry Foundation Class (IFC)

IFC is the most comprehensive international standard for BIM interoperability. Developed and managed by buildingSMART (evolved from the International Alliance for Interoperability (IAI)) since 1994, it has been registered by the ISO (International Organisation for Standardisation) as ISO16739. The target of this standard is to facilitate data sharing and exchange between different software applications used by various participants in AEC/FM industry for better interoperability (Fazio et al., 2007). IFC specifies a conceptual data schema and an exchange file format for BIM data, providing a comprehensive description of project structure, physical components, spatial components, analysis items, processes, resources, controls, actors, context definition (International Standards Organization, 2013). The conceptual data schema is written using EXPRESS data specification language. In parallel with the EXPRESS schema specification, the IFC data schema also provides an XML schema specification, the ifcXML. Currently it has been recognised as the mainstream standard for Open BIM and supported by more than 20 vendors (Zhiliang et al., 2011).

The latest release of IFC is IFC 4 that is fully integrated new mvdXML, enabling the extension of IFC to infrastructure and other parts of the built environment technology, BIM to GIS interoperability, and enhancing the thermal simulations and sustainability assessments. There are four levels in the architecture of IFC: the Domain, Interoperability, Kernel and Resource Layers, as shown in Figure 2.4 (buildingSMART, 2013).

- Resource layer: the lowest layer includes all individual schemas containing resource definitions, those definitions do not include a globally unique identifier and shall not be used independently of a definition declared at a higher layer;

- Core layer: the next layer includes the kernel schema and the core extension schemas, containing the most general entity definitions, all entities defined at the core layer, or above carry a globally unique id and optionally owner and history information;

- Interoperability layer: the next layer includes schemas containing entity definitions that are specific to a general product, process or resource specialization used across several disciplines, those definitions are utilised for inter-domain exchange and sharing of construction information;

- Domain layer: the highest layer includes schemas containing entity definitions that are specializations of products, processes or resources specific to a certain discipline, those definitions are typically utilised for intra-domain exchange and sharing of information.

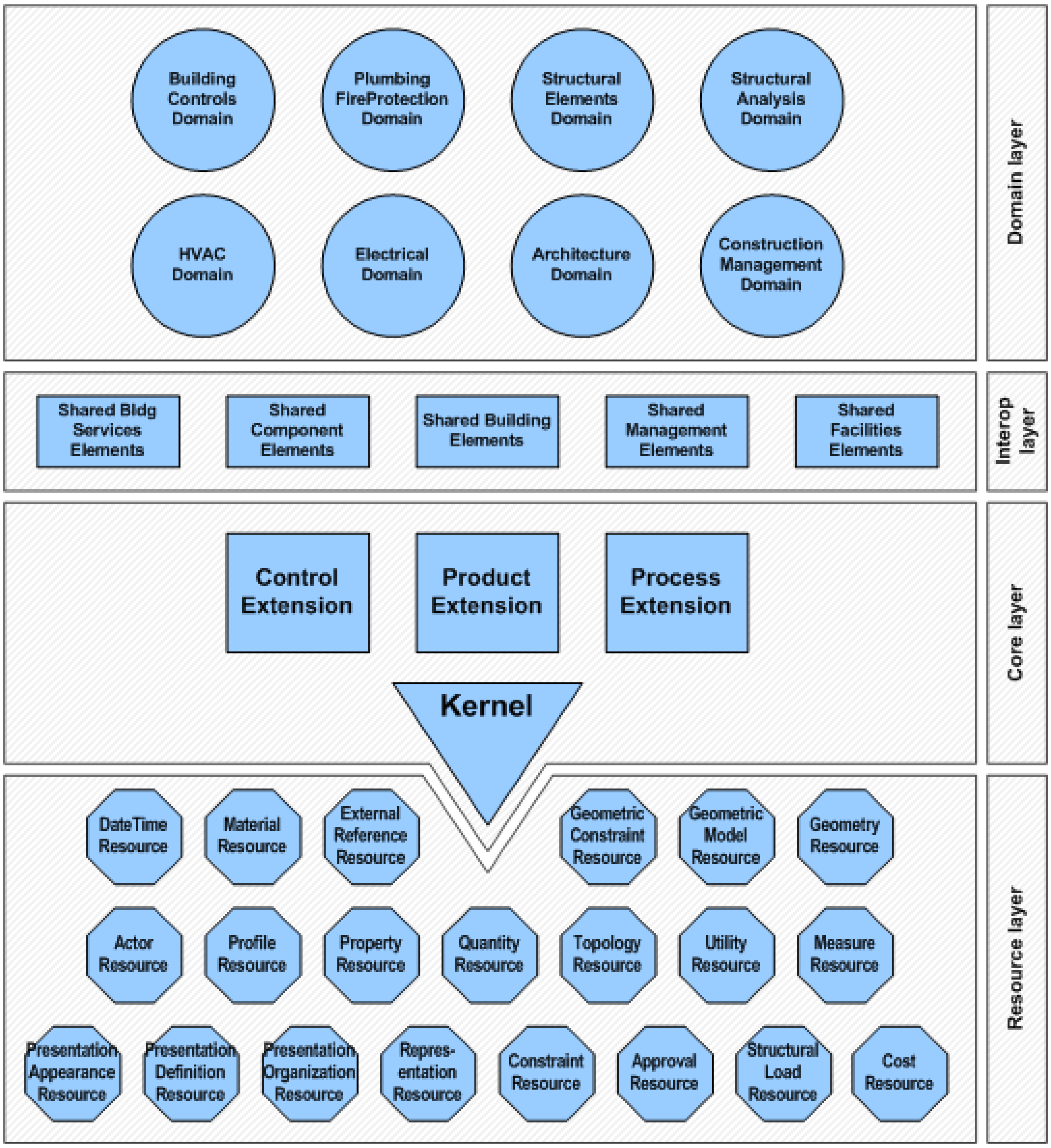


Figure 2.4 Architecture of IFC specification.

IFC has been implemented in various construction system integration for design, construction and facility management. Although the richness of information offered by IFC has been constantly improved since the release of IFC 2×3, the challenge remains in expression range (Pauwels et al., 2011a).

2.2.2.2 gbXML

The gbXML (green building XML) is developed for information exchange between BIM models to energy simulation and analysis tools. It becomes one of the leading standards used in collaboratively integrated design, and supported by most of BIM applications such as Autodesk Revit and Bentley solutions. Compared with IFC data model representing building project related data, gbXML is commonly used for describing and transferring energy-related data. There is a number of applications utilising import/ export features of gbXML to achieve system integration between BIM and energy simulation tools. However, the interoperability issue still remains and has been identified by Osello et al. (2011). Their research reported that changes occurred to the original architectural model during the data transfer process and iterative manual editing is needed.

2.2.2.3 ifcOWL

The amount and diversity of information is one of the most notable characteristics of building construction domain. The different understanding and interpretation of information by domain experts involved in a building project often lead to significant loss of time and resource, and increase the risk of errors in design. Among all the techniques adopted to tackle this problem, Building Information Modelling (BIM) is one of the most successful approaches (Eastman, 2011). However, recent research indicates that apart from an as-built model for visualisation, clash detection, building design and the construction, BIM merely improves the interoperability of information between applications (Becerik-Gerber and Rice, 2010). The development and adoption of Industry Foundation Classes (IFC) encompass the limitation to a certain extent by providing one neutral schema to describe building information (Liebich et al., 2007). However, in practical use, the data distortion and loss issue makes it nearly impossible to achieve the interoperability goal originally targeted (Pazlar and Turk, 2008, Verstraeten et al., 2008). Following barriers of IFC were found based on research presented in a number of publications (Jeong et al., 2009, Hietanen and Final, 2006, Beetz et al., 2009, Pauwels et al., 2011b):

- Limited expression range
- Difficulties in partitioning the information
- Multiple descriptions of the same information

The barriers seem mainly caused by the nature of the EXPRESS language underneath the IFC schema. As EXPRESS does not allow an easy and intuitive handling of information, it needs qualitative additional enhancements to make models described in this language sufficiently manageable (Pauwels et al., 2011b). Because the Semantic Web technology promises the means to connect all kinds of information into one Semantic Web, including their inherent semantics (Berners-Lee et al., 2001), it is logic to assume that it could provide for an appropriate alternative approach to deal with interoperability challenges.

The recent actions towards the development of an OWL version of the IFC schema evidence the effort of facing the community request to specify IFC in an ontology language (Terkaj and Šojić, 2015). Beetz et al. (2009) developed a Web Ontology Language (OWL) ontology named ifcOWL that enables the translation of the formal IFC schema into a Semantic Web graph, with improved partitioning of the information described in IFC. This initial effort has been extended by Pauwels with applications in many areas of AEC domain (Pauwels et al., 2011a). Kim and Grobler (2007) provided a simple structured presentation of ontology model mapping to the IFCs shown in Figure 2.5. In a recent research, Terkaj and Šojić (2015) presented an enrichment of the EXPRESS to OWL conversion patterns with OWL class expressions that specifically captured certain constraints of the IFC standard. The robustness of ifcOWL has been improved by supporting data integrity, consistency, and applicability across various industrial applications. The ifcOWL ontology is now built and maintained by the BuildingSMART Linked Data Working Group, and is published in-sync with IFC specification.

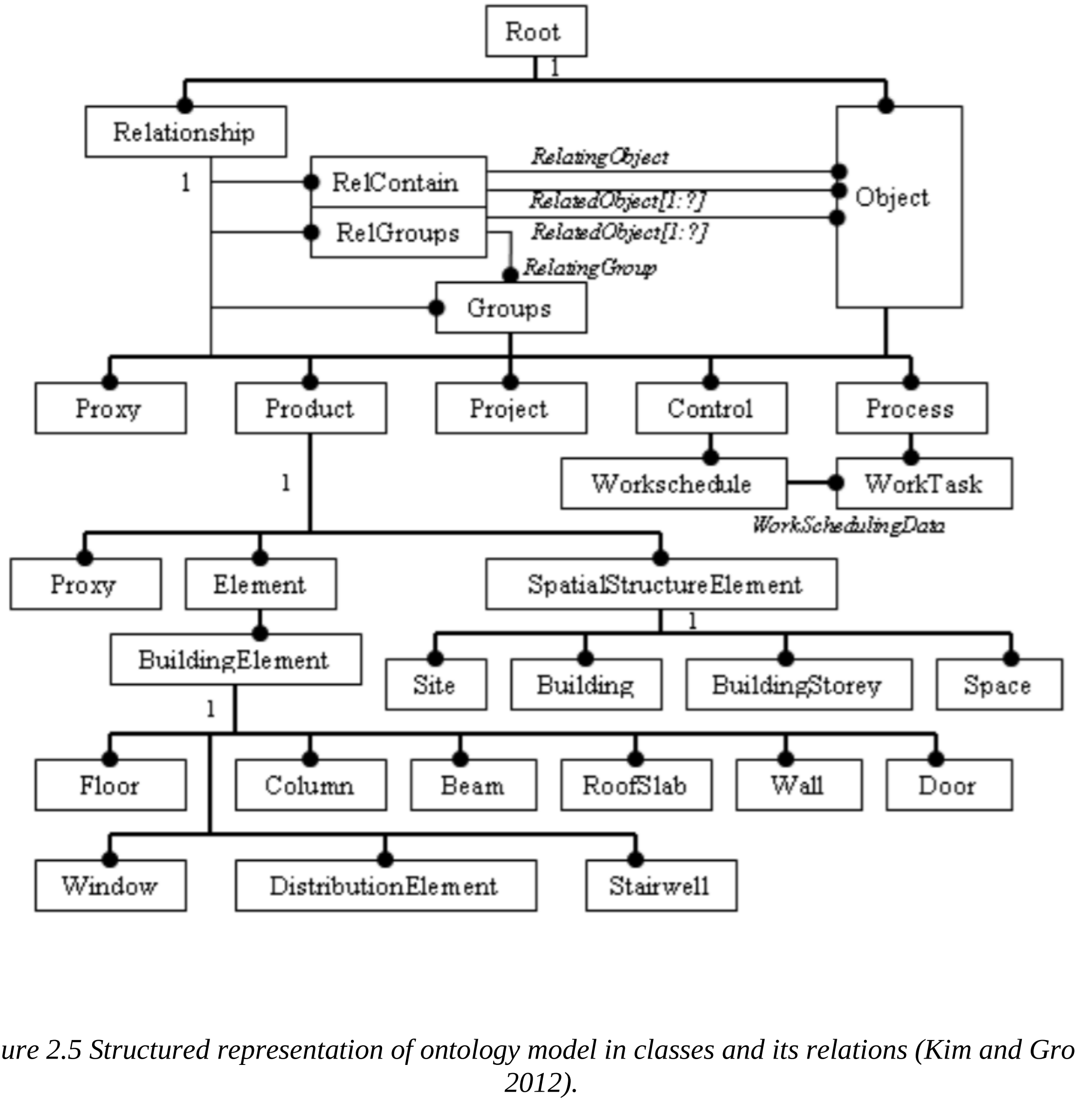


Figure 2.5 Structured representation of ontology model in classes and its relations (Kim and Grobler 2012).

2.2.3 System integration approaches in construction industry

2.2.3.1 Distributed objects/ components

The Object-oriented programming paradigm focuses on stressing modularity of data structure and code sharing to achieve programming efficiency. By using a centralised integration approach, it has been widely used for implementing integrated system. There are three major Distributed Objects standards: CORBA by the Object Management Group (OMG), COM/DCOM by Microsoft and Java RMI. The majority of agent-based system is deployed using Distribute Object technologies.

2.2.3.2 Software agents

Software agent is one the most popular technologies adopted to system integration and collaboration. In fact, most of the agent-based systems are implemented using Distributed Object technologies. This approach is suited best for applications that are modular, decentralised, changeable, ill-structured, and complex, because of the simplification of the architecture of the software systems and being proactive object systems. The benefits from adopting an agent-based system is better description of the real word by focusing on objects instead of functions, which allows flexible simulations and leads to better response and improved software reusability. The ability of coping with dynamical change allows agent-based system to handle rapidly changing situations.

- Anumba et al. (2002) discussed the use of agent technology in collaborative design and then presented the key features of an agent-based system for the collaborative design of portal frame structures, allowing for peer to peer negotiation between the design agents.

- Khamphanchai et al. (2015) proposed a building energy management (BEM) platform based on Multi-agent system (MAS). The proposed platform aims to improve energy efficiency, reduce energy consumption, and foster demand response (DR) implementation by controlling three major loads in buildings, including HVAC, lighting and plug loads.
- Labeodan et al. (2015) provides an overview of the application of multi-agent systems in building operations for coordination of various building processes and buildings interaction with the smart-grid.

2.2.3.3 Web-based systems

The World Wide Web (WWW) was initially developed for globally information sharing. It provides a centralised information integration approach using a shared Web server or a central database located on the Web server. Because of the simple client-server system architecture and mature Web development tools, developing and deploying a Web-based system takes very short time for daily management task of construction project. Therefore, the Web-based system has been actively developed for commercial use in construction market and implemented in many companies. In an integrated system for building design, the Web-based system is able to engage owners, architects and engineers into an interaction that encompasses a range of activities including geometric and semantic product modelling, design representation, user-interaction, and design browsing and retrieval. However, the complexity of collaboration in construction project requires more active assistance beyond information access. For example, the designer and engineer need to coordinate remotely. It is essential to involve translation of terminology among disciplines, locating/ providing generic analysis services, prototyping services, and project management in this coordination. This requirement is beyond the capability of basic Web technology. Thus, the Web servers need to be implemented as intelligent software agents acting as repositories of information but also systems to engage users in active dialogs while providing remote services in order to solve complex engineering problems.

2.2.3.4 Web services and a Semantic Web

One of the shortages of Web server approach is that it is only able to reply to the request from users, rather than to actively send data/ information to users or other servers. W3C proposed Web service technology to overcome this shortage. A Web service is a software system designed to support interoperable machine-to-machine interaction over a network. The Semantic Web has been further proposed as an evolving extension of the Web in which Web content can be expressed not only in natural language, but also in a format that can be read and used by software agents (The World Wide Web Consortium (W3C), 2015). The advent of web services and the semantic web have opened up opportunities for a new generation of interoperable systems on the web (Anumba et al., 2008).

In recent years, a large and growing number of literature has investigated the applications of Semantic Web technologies, especially the applications of ontology (D'Aquin et al., 2008). It has been widely used in knowledge engineering, artificial intelligence and computer science; in applications related to areas such as knowledge management, natural language processing, e-commerce, intelligent information integration, bio-informatics, and education (Gómez-Pérez et al., 2004). Considerable amounts of research have applied ontologies across various domains such as medicine (Chen et al., 2012), biology (Ashburner et al., 2000), transportation (Abanda et al., 2011b), agriculture (Mawardi et al., 2013) and economy (Yoo and No, 2014).

Ontology as an emerging Semantic Web technology surely has drawn researchers’ attentions from building construction industry due to the increasing demand of efficient knowledge management, information integration and better interoperability (Svetel and Pejanović, 2010). Compared with the IFC used for BIM data models, the ontology-based approach has a number of advantages:

- IFC is limited to share and exchange data with domain outside construction project and facility management, while the interoperability of ontology enables linking other structured data to building information model.
- The insufficient ability of IFC in representing some domain specific data, for example the energy-related data can be improved by ontology which can flexibly define concepts and relationships in target domain.
- IFC lacks semantic clarity in mapping entities and relationships, resulting in multiple definitions to map the same information between different federated models. Ontology provides a formal and consistent taxonomy and classification structure to map concepts between domains.
- Compared with the EXPRESS language used for IFC specification, the XML-like OWL language used in ontology is easier to understand and update.
- More importantly, the ontology provides reasoning function for automation information processing and decision support. Furthermore, the reasoning could be further leveraged by adopting semantic rules.

The endeavour of adopting the Semantic Web technologies has been well documented. In 2013, Abanda et al. (2013b) conducted a comprehensive review of over 120 refereed articles on built environment Semantic Web applications, which reflects significant progress being made theoretically and practically in building construction sector, and a trend of shifting from traditional construction applications to Semantic Web based integrated applications. One year later, Grzybek et al. (2014) provided a sufficiently detailed feasibility study with a literature review of 105 papers concerning the ontologies used in the building sector. This section provides a review of some recent projects on the application of the Semantic Web in system integration and interoperability. A review of the Semantic Web technologies and applications in construction sector is detailed in section 2.3.

- Boddy et al. (2007) reviewed the computer integrated construction research, revealing a strong focus on data and application integration. They proposed a process driven approach by integrating software agents and the Semantic Web services.
- Yang and Zhang (2006) presented an approach and its software implementation for the development of building design objects with semantics of interoperable information to support semantic interoperability in building designs. The novelty of the approach includes its incorporation of building design domain ontology, object-based CAD information modelling, and interoperability standard to make building information models and model data semantically interoperable.
- Anumba et al. (2008) presented an ontology-based approach to project information management in a semantic web environment, including a framework for semantic web-based information management (SWIMS).

- The e-COGNOS project (COnsistent knowledGe management across prOjects and between enterpriSes in the construction domain) proposed a prototype ontology for the construction domain to support semantic knowledge management including semantic indexing, information retrieval and ontology-based collaboration (Wetherill et al., 2002, Lima et al., 2003). It consists of about 15000 concepts. The scope of the ontology covered seven major themes (Ei-Diraby et al., 2005): (1) Project, (2) Actor, (3) Resource, (4) Product, (5) Process, (6) Technical Topics (conditions) and (7) Related Disciplines (work environment).

- Pauwels et al. (2011a) investigated interoperability issues in AEC industry and presented a AEC description framework based on semantic web technology comparing to the BIM approach. They indicated the potential of solving the issue of interoperability more appropriately using the Semantic Web approach as a valid alternative approach.

- Curry et al. (2013) proposed the use of linked data as an enabling technology for cloud-based building data services. Linked data technology leverages the existing open protocols and W3C standards of the Web architecture for sharing structured data on the web. With linking building data in the cloud, it is possible to create an integrated well-connected graph of relevant information for solving data interoperability problems and managing a building holistically.

2.2.3.5 Ontology-based BIM system

Since the early 2000s, building information modelling (BIM) has been used through the entire project life cycle to facilitate effective project collaboration and integration of data to support project activities (Karan and Irizarry, 2015). Despite the success of BIM in building visualisation, simulation and design collaboration, it is necessary to extend the interoperability of BIM system to integrate structured data/ information and knowledge from various resources. The Semantic Web technologies especially ontologies become increasingly appealing to the BIM researchers, because ontology offers many benefits (conclude in section 2.2.3.4) such as semantic clarity in mapping concepts and relationship between different federated models. The formal and consistent taxonomy and classification structure would extend the overall interoperability of BIM tools (Venugopal et al., 2015). Although using ontology for integration with BIM models is a relatively new topic, there has been a wide range of applications using this approach. The following cases illustrates some recent developments.

- A study conducted by Karan and Irizarry (2015) used the Semantic web technology to convey meaning, which was interpretable by both construction project participants as well as BIM and geographic information systems (GIS) applications processing the transferred data. The building's elements and GIS data are translated into a semantic web data format. Then a set of standardized ontologies was developed for construction operations to integrate and query the heterogeneous spatial and temporal data. Finally, this study used a query language to access and acquire the data in semantic web format.

- Mignard and Nicolle (2014) developed a semantic extension to the BIM called UIM (Urban Information Modelling) to solve the heterogeneity problem between BIM and GIS. This extension defines spatial, temporal and multi-representation concepts to build an extensible ontology. The knowledge database can be populated with information coming from standards like IFC and CityGML.

- Zhang et al. (2015) proposed a construction safety ontology to formalise the safety knowledge, and developed a prototype application of ontology-based job hazard analysis (JHA), enabling interaction between safety ontology and BIM.

- A research by Lee et al. (2014) proposes an ontological inference process to automate the process of searching from BIM data to find items suitable for building elements and materials. To enable automated inference, this study establishes (1) a work condition ontology that consists of the determinants required to select work items, (2) a work item ontology, which consists of the factors defining the tiling method, and (3) semantic reasoning rules.

- Costa and Madrazo (2015) presented an application of Semantic Web technologies to connect BIM models with a catalogue of structural precast concrete components. In this study, different heterogeneous data sources related on building products can be integrated, and a semantic BIM services has been developed to support structural modelling.

2.2.3.6 Hybrid integration approach

The system integration approaches reviewed in this section aim to solve the interoperability problems and make building information models understandable and shareable across multiple design disciplines and heterogeneous computer systems. The development of smart building technologies demands new integration infrastructures that can incorporate multiple system integration approaches (software agent, BIM model, ontology, wireless sensor, etc.) to provide advanced and intelligent facility management. Dibley et al. (2011, 2012, 2015) introduced an integrated framework that includes a ZigBee based sensor network and multi-agent software (MAS) components with ontology support (Figure 2.6). The different software agent types have been developed to work with sensor hardware to conduct resource negotiation, to monitor building space and to reason about its usage through real time ontology model queries.

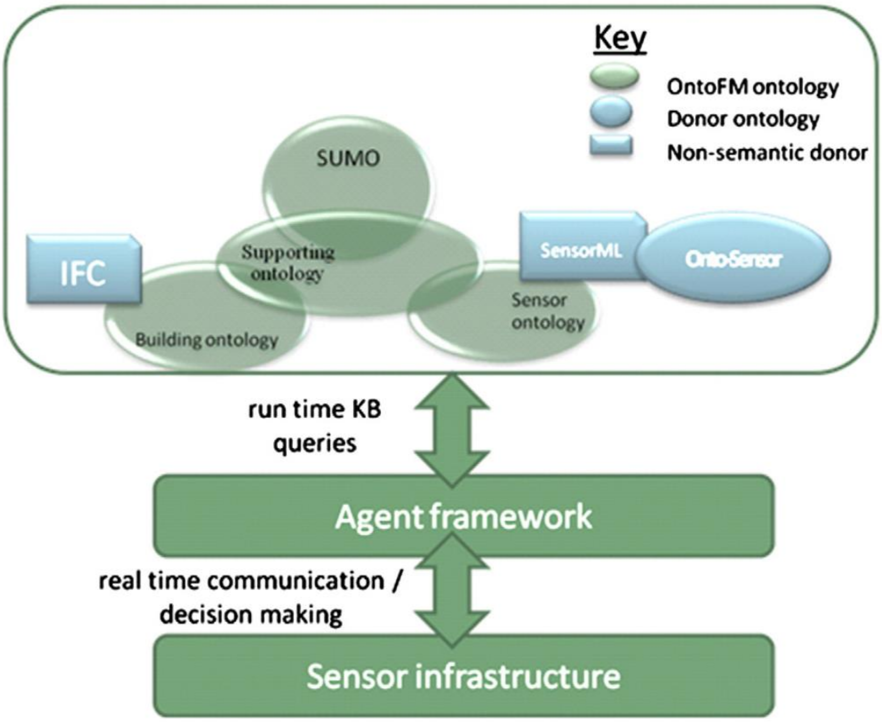


Figure 2.6 OntoFM ontologies, interrelationships and dependencies (Dibley et al., 2012)

In this thesis, the Semantic Web approach will be used for develop a holistic system that integrates structural design knowledge and sustainability information. The main reason to choose this approach is the semantic interoperability that ontology-based system offers, which the concepts, constraints and relationships in these two domains (structural design and sustainability) can be formally expressed. The proposed system can better assist in building design decision making, and is possible to be further leveraged to collaborate with other software system. In the ensuing section, the Semantic Web and its applications in construction domain are explored.

2.3 The Semantic Web technology

2.3.1 Current web

2.3.1.1 Background

It has been more than 20 years since Tim Berners-Lee invented the World Wide Web (WWW) (Berners-Lee et al., 1994). The birth of World Wide Web has become one of the greatest success in information world and human history. It has offered enormous opportunities to access electronic documents and resources stored in this virtual information space. In this new virtual space, items of interest are refereed as resources and identified by global identifiers called Uniform Resource Identifiers (URI), and can be accessed by the users of internet. As a result, it enables an exponential production of electronic document and growth of web users. During the last decades, the WWW has grown to the largest distributed information repository in human history (Tah and Abanda, 2011), where contains about 3 billion static documents and being accessed by over 500 million users from all around the world by an estimation in 2007 (Bui et al., 2007). Today, the web is acting as a fundamental platform for sharing information across billions of agents in different geographical locations.

However, the efficiency of current web in terms of knowledge sharing is still a debatable topic. It is partly as a reason that many researchers recently have increasingly shown interests on technologies that are able to enhance the efficiency of current web. Therefore, the Semantic Web technologies emerged to meet such demand. The potential of the Semantic Web technologies has drawn many attentions from different industries, such as bioinformatics, medicine, publishing, finance and energy (Antoniou and Harmelen, 2008, Warren and Alsmeyer, 2005). Consequently, the success of the Semantic Web in these areas inspires the professions in construction industry. A large number of researchers from construction sector shown keen interest and have make great efforts to adopt Semantic Web technologies in various applications (Abanda et al., 2013b). The popularity of the Semantic Web in a wide range of research areas would enhance the rationale of this study. Therefore, in order to demonstrate the opportunities and advantages of the Semantic Web, it is necessary to examine the limitations of current web technologies.

2.3.1.2 The problems of current web

The search engines have been playing a crucial role in current web. However, searching the web with the majority of today's search engine still suffers from many problems raised from the general characteristics of the Internet and web content, including difficulties due to the enormous size of the web and rapidly changing content, the deep web and probably one of the most challenging problem – the lack of semantics(Breitman et al., 2007) (Szeredi et al., 2014):

- The enormous size of the web, containing billions of pages and terabytes of data poses an unprecedented challenge to the effective information retrieval from the Internet. Not only the size but the web content changing minute by minute makes searching and visiting web pages on the Internet a time-consuming task. The current searching techniques, for example, using key words to search on the web can be found quite frustrating. Because the search results offered by the search engine always contain a huge amount of irrelevant entries, which results in a very low precision. Therefore, the web users are often overwhelmed by more or less irrelevant information and have to dig into thousands of web pages with confusing contents, reading the contents to find useful information. Moreover, the presentation of search results is a list of references to individual web pages where many entries belong to the same website. Or in the converse case, the relevant information is dispersed in many entries, which is challenging to verify the complete set of relevant entries.

- The deep web is another problem that is frequently discussed these days. The interpretation of “deep web” is either database content only available via web form submissions or documents available in non-textual formats. Data stored in databases is accessed by filling web forms and submitting queries, a significantly different way compared to the direct access we are used to in the case of web pages. Such content is unavailable to search engine.

- One of the most crucial problems of current web search is the lack of searching based on the semantics of documents and queries. This deficiency has resulted in a number of consequent problems. The first one is language problem. The search engine relies heavily on the actual representation of textual information (Szeredi et al., 2014). In other words, from the perspective of search engine, the input of search query has no meaning but a string of words. As a result, the quality of search results is very dependent on the key words used. It is common that the vocabulary Web users use to formulate their search are different from the relevant web pages adopt. For example, some web users tend to use “standards” instead of “protocol”. Hence, it is not easy to find the best results that use terms “TCP/IP” and “protocol”. This problem can be formulated at a higher level of abstraction that language of documents and query can be ignored. Normally the language of results matches that of the query. For example, if we seek answer to the question about human organs, the results are pages in English. In fact, it is possible that the results containing the most useful information might not be English but a Japanese page, or even pages with no regard to the language or the format, for example, an image depicting the human body and its organs. Another problem of semantics is pictures and multimedia contents. As classified as non-textual documents, these contents usually cannot be automatically extracted only if they contain labels or texts that can be extracted by image-processing algorithm to match the query. Additionally, the understanding of background knowledge and reasoning function are another characteristics lacking in current search engines.

Besides the weakness of the search engines mentioned above, other limitations of current web are also noted including maintenance of web resource and presentation of information (Yu, 2007, Antoniou and Harmelen, 2008). To summarise, much more than textual search in a huge mass of data is needed to make the search engine act like a thinker, being aware of the meanings of the concepts and the relationships between concepts.

There are some solutions available for the problems. One way to manage size and variability of the web is use meta search engine and focused crawling. To deal with the non-textual information in deep web, some techniques use human intelligence to extract content. Although the satisfactory solutions exist in many cases, the way to grasp the semantics of the web remains an open question. Of all these solutions, the Semantic Web has the potential for significant progress. The major techniques of the Semantic Web for overcoming this problem include catalogues, query expansion engines and meta-information. The basic idea is to capture the semantics of web contents, to organise the contents according to its meaning by associating with meta-information in standardised form, and to represent the web in the form that is possible to understand and reason by computers.

2.3.2 The Semantic Web

2.3.2.1 What is the Semantic Web?

In order to overcome the limitations of current web, the initiative of the Semantic Web was proposed by Tim Berners-Lee (Berners-Lee et al., 2001). A few scenarios based on future web technology were described in his revolutionary article, which improved the current web 2.0 by adding a semantic layer (Berners-Lee et al., 2001). Thus, the data on the web could be interacted and exchanged without considerable effort by parties (for example software agents) to help human solve problems and carry out time-consuming tasks. The key technology that is able to realise these scenarios is the Semantic Web.

The Semantic Web is not parallel development of the current web. It is an extension evolving from current World Wide Web to enable intelligently search, combine and process web content by computer based on its meaning. Because it primarily focus on data exchange, the Semantic Web has been described as an effort for a “web of data” (Breitman et al., 2007). The W3C describes the vision of the Semantic Web as follow (W3C, 2015). The Semantic Web is to provide an infrastructure for the meaningful contents on the web pages, creating an environment where data can be shared and reused across application, enterprise, and community boundaries, and providing a platform where machine can quickly retrieval and process the data by using inference and query for sophisticated tasks (Zhou et al., 2011).

2.3.2.2 The motivation of Semantic Web technology development

The limitations of current web are not the only inspiration of emergence of the Semantic Web. Hitzler et al. (2010) summarised three motivations that provide conceptual foundations of the Semantic Web.

- The first motivation is that the Semantic Web offers a general approach to describe the complex reality of the world in a simpler way by building abstract models. In general, a model is a simplified description of certain part of reality. In this study, a model is referred in the context of scientific modelling. During last centuries, numerous models with increasing complexity and diversity have been developed, which significantly influence today's Semantic Web technologies. This development also leads to a speedy growth of modelling languages, for example the Unified Modelling Language UML used in software engineering in computer science.

- The second motivation is the requirement of computing with knowledge, which allows computers to draw meaningful conclusions from knowledge model. One of the most successful examples is the knowledge-based system, which enables computer to manage human knowledge for various purposes such as advisory and tutorial system in a wide range of areas. Especially in medicine and biology area, knowledge-based system has established a solid position that takes large proportions of human experts' job (Pandey and Mishra, 2009). Encouraged by the convincing scientific findings and the rapid development of computer technologies, researchers have taken a large amount of effort to implement knowledge-based systems for general purposes.

- Finally yet importantly, the most commonly known motivation is efficient information exchange. The information exchange on the web requires standard data formats and structure for web content. The current approach of WWW is insufficient for searching the ever increasing amount of web content and describe the complexity of current development.

In reality, it is nearly impossible to realise Semantic Web to all human knowledge on the web. From a practical point of view, the former two motivations building models and calculating with knowledge are more reasonable for developing Semantic Web technology. In other words, the Semantic Web technology is similarly useful for applications beyond the scope of web. In order to achieve this goal, it is necessary to develop semantic languages to express machine readable information for documents; more importantly, to establish a new architecture for the languages to support finding, access, presenting and maintaining information and developing applications of Semantic Web (Fensel, 2003). This architecture is referred to “the Semantic Web architecture”.

2.3.2.3 The Semantic Web architecture

The development of Semantic Web adopts a layered approach, each step building a layer on top of another. The language in higher layer exploits the feature and extends the capability of the layer below. This hierarchy of language is the Semantic Web architecture (Berners-Lee, 1996). Antoniou and van Harmelen (2008) justified this step-by-step approach and argued it enables an easier way to achieve consensus on small steps without attempting too much at once. Figure 2.7 shows the model that describes the main layers of the Semantic Web design and vision.

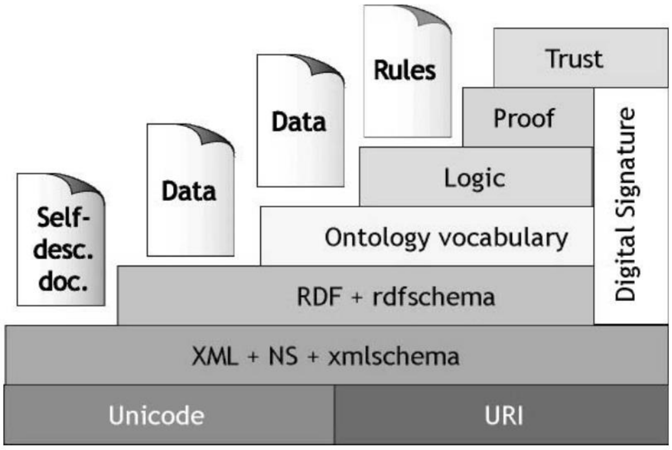


Figure 2.7 A layered approach to the Semantic Web (Antoniou and van Harmelen, 2008).

The Semantic Web architecture is composed of seven layers.

- The bottom layer named as reference layer uses Unicode and Universal resource identifier (URI) to provide references to the objects in ontology;
- The syntax layer is composed of XML, name space and XML Schema. The eXtended Markup Language (XML) is a language that structured web documents with a user-defined vocabulary. It is particularly suitable for sending documents across the web.
- RDF is a basic data model for writing simple statements about web objects. The RDF data model does not rely on XML, but RDF has an XML-based syntax. Therefore, in Figure 3.1, it is located on top of the XML layer. RDF Schema provides modelling primitives for organising web objects into hierarchies. Key primitives include classes and properties, subclass and sub-property relationships, and domain and range restrictions. RDF Schema is based on RDF. RDF Schema can be viewed as a primitive language for writing ontologies.

- Ontology languages expand RDF Schema and allow the representations of more complex relationships between web objects.

- The logic layer is used to further enhance the ontology language for writing application-specific declarative knowledge.

- The proof layer involves the actual deductive process as well as the representation of proofs in web languages and proof validation.

- Finally, the trust layer will emerge through the use of digital signatures and other kinds of knowledge, based on recommendations by trusted agents or on rating and certification agencies and consumer bodies. Being located at the top of the pyramid, trust is a high-level and crucial concept: the web will only achieve its full potential when users have trust in its operations and in the quality of information provided.

The composition of classical layer stack is currently debatable (Horrocks et al., 2005). Figure 2.8 shows an alternative layer stack that considers recent developments. The main difference from the stack in Figure 2.7 is integrating rules with OWL, which suggests that future versions of this architecture could include a decidable subset of SWRL, and a principled integration of OWL and Answer Set Programming (Eiter et al., 2004, Motik et al., 2004, Rosati, 2005).

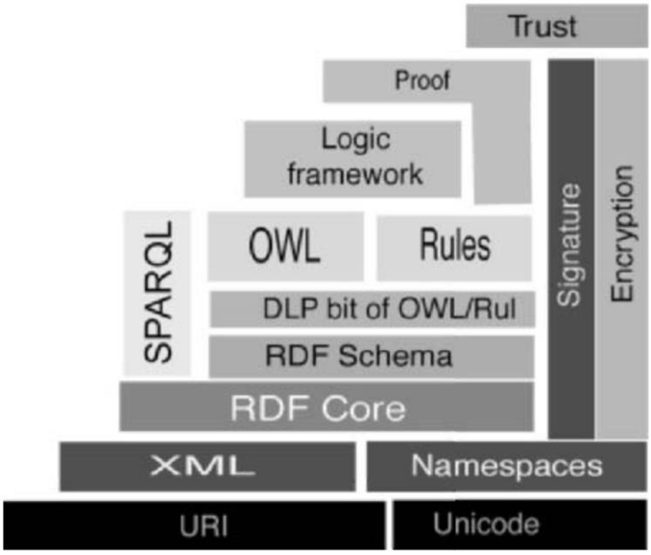


Figure 2.8 An alternative Semantic Web stack (Antoniou and van Harmelen, 2008).

2.3.3 Ontology and Web Ontology Language (OWL)

2.3.3.1 What is ontology?

Ontology is considered as a backbone of Semantic Web development (Taye, 2010). As one of the main motivations of ontology development is for knowledge sharing and reuse across different domains (Guarino, 1997), it provides a vocabulary and a framework to structurally model knowledge of a given domain in a format that can be processed by both machine and human. Originally a term from the discipline of philosophy, ontology means “the study or theory of the explanation of being” (Taye, 2010). It was commonly used to describe the existence of instances or things in the real world, as Lowe (1995) explained in his study:

“The set of things whose existence is acknowledged by a particular theory or system of thought”.

From early 1980s, ontology begun to draw the experts' interests from artificial intelligence community. The meaning of ontology had been changed. Neches and colleagues (1991) firstly defined ontology as follow. This definition provides a vague guide describing a number of tasks for developing ontology, including identifying terms and relations between terms.

"An ontology defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary".

By the end of 1990s, ontology had been widely discussed in computer science area and used in a variety of areas and applications, including enterprise modelling, e-commerce and knowledge management (KM) (Swartout and Tate, 1999, Welty and Guarino, 2001, Rezgui, 2007b). Along with its applications in various areas, the definitions of ontology have been evolving into many different versions over time. Corcho et al. (2003) argued that, from his perspective the best definition capturing the essence of an ontology is the one given by Gruber in 1995, which is also one of the most quoted definitions of ontology (Gruber, 1995):

"An ontology is an explicit specification of a conceptualisation".

On the basis of Gruber's definition, the meaning of ontology has been further explained or modified. Borst (1997) modified Gruber's definition by emphasising the nature of sharing:

"Ontologies are defined as a formal specification of a shared conceptualisation".

Studer and colleagues (1998) elaborated every term in Gruber's and Borst's definitions as follows:

“Conceptualisation refers to an abstract model of some phenomenon in the world by having identified the relevant concepts of that phenomenon. Explicit means that the type of concepts used, and the constraints on their use are explicitly defined. Formal refers to the fact that the ontology should be machine-readable. Shared reflects the notion that an ontology captures consensual knowledge, that is, it is not private of some individual, but accepted by a group”.

Guarino and Giaretta (1995) concluded and analysed seven definitions of ontology. They went a step forward to consider building ontology as making a logic theory. In that paper, ontology was defined as a *“logical theory which gives an explicit, partial account of a conceptualization”*.

Guarino et al. (2009) specified the characterisations of ontology and demonstrated the relationships between reality, conceptualisation and ontology model in Figure 2.9. In his theory, an ontology is

“a set of axioms, i.e., a logical theory designed in order to capture the intended models corresponding to a certain conceptualization and to exclude the unintended ones. The result will be an approximate specification of a conceptualization: the better intended models will be captured and non-intended models will be excluded”.

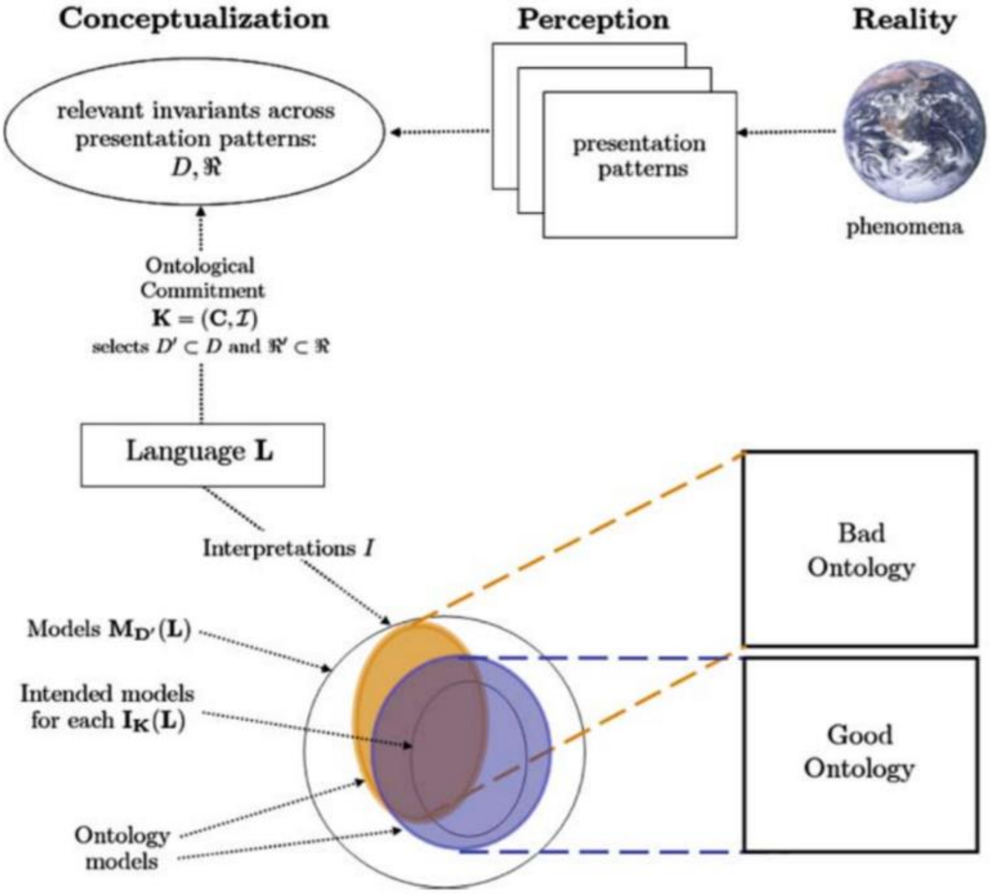


Figure 2.9 Relationships between reality, conceptualisation and ontology model (Guarino et al. 2009).

From a practical point of view, a typical ontology can be represented as following form (Hu et al., 2013):

$$O = < C, P, R, I, A >$$

where *O* is the ontology describing the concepts and their relations in domain, *C* is a collection of concepts, *P* is a collection of properties of the concepts, *I* is a collection of individuals of the concepts in *C*, *R* is a collection of relations between the concepts, and *A* is the collection of axioms which are used to restrict the properties and relations.

2.3.3.2 Why ontology?

One of the main drawbacks of information management approach in current web is the lack of semantic links between terms in various domains. The ambiguity of terms is difficult for computer to understand and always required human interpretation. Ontology has a number of attractive features that could potentially address this issue: explicitly defined common vocabulary, formal taxonomy, semantic knowledge that can be processed by machine.

To eliminate the ambiguity and imprecision of terms used in natural language, ontology not only defines the terms in a specific domain, but also describes the relationships between these terms. For example, it is difficult to identify what OWL refers to in current web context. The search results of using keyword "OWL" varies from species of bird to a web language. In the context of ontology, it becomes easier to distinguish the results based on their semantics and relationships. Furthermore, Ontology provides a hierarchy of concepts in a particular domain. The strictly defined taxonomy formally specifies the relations of superclass and subclass, which ensures the consistency in the use of ontology for reasoning. The common vocabulary and formal taxonomy provide a sharing understanding of terms for different agents, which facilitates more efficient knowledge sharing and reusing. More importantly, the ontological representation of knowledge; for instance, OWL ontology offers an effective way for automated information processing by encoding knowledge in a semantic form.

2.3.3.3 Differences between ontology and taxonomy

A taxonomy uses generalisation hierarchy structure to classify terms. There are two fundamental difference between taxonomy and ontology. Firstly, it only allows father-son relationship by eliminating other relationships such part-of, cause-effect, association and localisation. Furthermore, defining attributes of terms is not supported in taxonomies. In contrast, ontology is more flexible to describe relationships and define attributes (Breitman et al., 2007). According to Noy and McGuinness (2001), there are three unique properties that only ontology maintains:

- Strict sub-concept hierarchy. All the concepts are organised in a tree structure where terms must follow generalisation relationship and every instance of a class must be an instance of upper class;
- Ambiguity-free interpretation of meaning and relationship. The properties defined by users could be limited to certain domains. More expressive relationships such as disjunction may be used for sophisticated ontologies.
- The use of a controlled, finite but extensible vocabulary.

2.3.3.4 Differences between ontology model and object-oriented model

An ontological model shares many similarities with the traditional conceptual model but there are also differences. Distinguishing the differences would generally facilitate the development of ontological models. The major differences have been listed (F. H. Abanda 2011):

- An ontology model reflects the structure of the fact in the world; while the object-oriented model reflects the containment of data and behaviour;
- A concept in ontology model is a collection of instances; while a class in object-oriented model is a blueprint for defining instances;
- The instances in ontology model can be created in design or run-time; while the instances in object-oriented model can only be created at run-time;

- The property of a concept in ontology model could exist independently; while the behaviour in object-oriented model is embedded in a class definition and cannot be used independently;

- The ontology model is based on open world; while the object-oriented model is based on a closed world;

- The ontology model natively supports automated reasoning from knowledge; while the object-oriented model does not.

2.3.3.5 Evolution of ontology language

In recent years, several mark-up languages have been developed for realising the Semantic Web (Pulido et al., 2006). The development of web ontology description languages is evolving according to the layered approach introduced in previous section (Corcho and Gómez-Pérez, 2000). Based on the RDF/RDF-S, several ontology description languages such as SHOE, Oil, DAML, DAM+Oil, and OWL have been defined gradually.

The simple HTML Ontology Extension (SHOE) by University of Maryland was the first ontology description language created for the Semantic Web. The goal of this language was to allow agents and software to use tags to retrieve and store knowledge directly from HTML pages (Pulido et al., 2006). This approach offered the ability to add semantic content to web pages by extending HTML with a set of object-oriented tags, and associates meaning with content by committing web pages to existing ontologies (Luke et al., 1997).

The Ontology Inference Layer (Oil) (Horrocks, 2000), which was an outcome of On-To-Knowledge Project (Fensel et al., 2000), was based on three elements: frame-based systems, description logics, and web standards (Fensel et al., 2001). Firstly, the central modelling primitives of frame-based systems were frames with properties. Secondly, description logics had been developed in knowledge representation research for describing knowledge in terms of concepts and roles. Thirdly, Oil was developed as an extension of the RDF and its extension schema (RDFS), which provided a standardised syntax for writing ontologies and a standard set of modelling primitives.

Another endeavour by Defense Advanced Research pROJECTS agency (DAPPA) was the DAPPA Agent Markup Language (DAML) aiming to establish the infrastructure of the Semantic Web (Lassila et al., 2000). Also extended from RDF/RDF-S, the DAML constituted two portions, the ontology language and a language for expressing constraints and adding inference rules. The combination of Oil and DAML created a single language DAML+Oil (McGuinness et al., 2002, Horrock, 2001). Additionally, the Inference Language (DAML-L) was proposed as a logical language with a well-defined semantics and the ability to support rules for reasoning.

As an endeavour of experts from Web Ontology Working Group, the Web Ontology Language (OWL) has now become the standard ontology language for the Semantic Web (McGuinness and Harmelen, 2004). The ensuing section further explains OWL.

2.3.3.6 OWL

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. Despite its popularity in Semantic Web community, there are some drawbacks that OWL has suffered from its expressiveness (Berendt et al., 2004):

- Some constructs are very complex; this explains why it derives to three sublanguages;
- Reasoning is not efficient as there is a trade-off against time-complex cost.
- It is not easy to use; however, this motivates to create software tools to use it.
- It is not intuitive; expert knowledge is needed to build efficient knowledge constructions.

Therefore, to extend the flexibility of OWL and satisfy constraints of different domains, three sublanguages of OWL with different degrees of expressiveness are developed for users to select (Horrocks et al., 2003).

- OWL Full - OWL Full is the language of the three containing all of RDFS with maximum expressiveness. However, it is undecidable due to lack of restrictions and semantically difficult to understand and work with (Hitzler et al., 2010). 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 is highly decidable yet has less expressiveness that only permits cardinality values 1 or 0. It is suitable for the need of a classification hierarchy with simple constraints.

There is an increasing trend of adoption of OWL in many applications of various domains. The different version of OWL provides choices for developer to select the appropriate one depending on the system requirements. Based on the facts that the OWL Full is hard for reasoning software to support complete reasoning and OWL Lite is not competent to capture class hierarchies, OWL DL has been adopted as the ontology language in this study.

2.3.3.7 Classification of ontology

A number of references have proposed different classifications for ontologies. McGuinness (2003) proposed a classification based on internal structure and contents of the ontologies. In this classification, the spectrum of ontologies ranges from lightweight to heavyweight based on the comprehension and complexity of elements.

Guarino (1998) proposed a classification based on the generality of ontologies:

- Upper level ontologies describe generic concepts which are independent to any specific domain and could be reused for the new ontology development;
- Domain ontologies describe the vocabulary associated with a certain domain with specialisation of upper-level ontologies;
- Task ontologies describe the vocabulary required to perform generic task;
- Application ontologies describe the vocabulary of a specific application.

Gómez-Pérez et al. (2004) partially adopted the previous classifications and proposed one whose main criterion is the type of information the ontology represents. In this classification, the ontologies can be categorised as following eight types:

- Knowledge representation ontologies provide essential modelling elements for knowledge representation models;

- Generic and common ontologies provide a vocabulary to represent common-sense knowledge, such as classes, events, space and behaviours; for example, the Time Ontology stored in DAML public ontology library. It can be used to build ontologies in different domains;

- Upper ontologies describe general concepts;

- Domain ontologies describe concepts that could be reused in a specific domain;

- Task Ontologies describe the vocabulary related to a task or activity;

- Domain-task ontologies are a sub-type of task ontologies, which could be reused within one specific domain;

- Method ontologies describe the concepts and relationships associated with a process;

- Application ontologies extend the domain ontologies and task ontologies for a specific application. They consist of all the essential concepts to model the application.

According to the classification proposed by Gómez-Pérez et al., the ontology presented in this study can be categorised into the application ontology, as it is designed to carry out structural design task in sustainable building design domain.

2.3.4 Semantic Web Rule Language

RDF Schema, OWL and other knowledge representation languages are designed to specify descriptions of application domains (Breitman et al., 2007). They offer constructs to describe classes, properties, and relationships, in addition with constraints to capture class and property restrictions and to define complex classes (Alesso and Smith, 2006). In some cases, although the ontologies provide the basic reasoning, there is still a need of extending the reasoning capability of ontology to support knowledge services required by the Semantic Web (Eiter et al., 2008). Therefore, this is where are incorporated rules. The rule languages are designed to specify data transformation rules that define how to generate new facts from existing ones stored in knowledge base (Breitman et al., 2007). There are a number of rule languages developed for this purpose, such as Rule Markup Language (RuleML), TRIPLE and the Semantic Web Rule Language (SWRL).

2.3.4.1 SWRL

One of the limitations of OWL is that only structural inference such as subsumption and identity is provided (Walton, 2007). 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 (2004) 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 (Horrocks et al., 2004). 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 (Chandra and Harel,

1985) which have the form of an implication between an antecedent and a consequent. Both consist of conjunctions of atoms that are represented symbolically as:

Equation 2.1 Syntax of SWRL rule.

$$A_1, \dots A_{n-1}, A_n \rightarrow B_1, \dots B_{n-1}, B_n$$

where A_i and B_i are atomic formulas, and $i = 1, 2, 3, \dots, n$. 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).*

2.3.5 Querying in ontology

2.3.5.1 SPARQL

The requirement of conveniently accessing useful pieces of information in ontology promotes the development of ontology query language. A group of ontology query languages have been developed to facilitate the extraction of information from ontologies; for example, RQL, SeRQL and SPARQL. SPARQL is the most advanced query language (Prud'hommeaux and Seaborne, 2008). The SPARQL query language is a W3C candidate recommendation for querying RDF, and as such is becoming the standard query language for this purpose (Pérez et al., 2009). For this reason, it has been supported by most of the RDF query tools. A simple example of SPARQL query is given as follow:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
SELECT ?c
```

WHERE
{
?c rdf:type rdfs:Class .
}

This query retrieves all triple patterns where the property is *rdf:type* and the object is *rdfs:Class*. In other words, the execution of this query could retrieve all classes of the targeted ontology.

O'Connor and Das (2009) pointed out the shortcoming of SPARQL query language as it has no native understanding of OWL. To overcome this weakness, they proposed a concise, readable and semantically robust query language for OWL, SQWRL (Semantic Query-Enhanced Web Rule Language). The SQWRL query language is exploited in this study to extract information from ontology, and is examined in the ensuing section.

2.3.5.2 SQWRL

SQWRL is built on the SWRL rule language. SQWRL takes a standard SWRL rule antecedent and effectively treats it as a pattern specification for a query (O'Connor and Das, 2009). It replaces the rule consequent with a retrieval specification. SQWRL can be extended using SWRL's built-in facility. The built-ins are particularly useful to define a group of operators that can be adopted to specify retrieval constraints or requirements. Since syntactic extensions are not required to SWRL, existing SWRL editors can be used to generate and edit SQWRL queries. In addition, queries can be embedded in OWL ontologies because of the use of standard SWRL serialisation mechanisms. The core SQWRL operator is *sqwrl:select*. It takes one or more arguments, which are typically variables used in the pattern specification of the query, and demonstrate the answers of query in a table where the arguments are the columns of the table. For example, the following query retrieves all persons in an ontology with a known age that is less than 25, together with their ages:

Person(?p) ^ hasAge(?p, ?a) ^ swrlb:lessThan(?a, 25) → sqwrl:select(?p, ?a)	*Query 2-1*

This query will return pairs of individuals and ages with one row for each pair. Results can be ordered using the *orderBy* and *orderByDescending* built-ins. For example, a query to return a list of persons ordered by age can be written:

Person(?p) ^ hasAge(?p, ?a) → sqwrl:select(?p, ?a) ^ sqwrl:orderBy(?a)	*Query 2-2*

The antecedent of a SQWRL query on the left hand side operates like a standard SWRL rule with its associated semantics. For example, the atom *Person(?p)* will match not only all OWL individuals that are directly of class Person but will also match individuals that are entailed by the ontology to be individuals of that class. In fact, all variables that would be bound in a SWRL rules antecedent will also be bound in a SQWRL pattern specification. There is no restriction placed on the left hand side of a SQWRL query. In other words, any valid SWRL antecedent is a valid SQWRL pattern specification.

In order to fully recognise the capabilities and reap the benefit of Semantic Web technologies, it is necessary to review the domains in construction sector that Semantic Web has been applied, and also the approach and embedded technologies in those applications. The review is conducted in the following section.

2.3.6 Applications of the Semantic Web technology in construction sector

Having reviewed the fundamental theory of the Semantic Web, in this section, we will further explore how Semantic Web technologies have been exploited to develop applications. Besides the applications of the Semantic Web in interoperability (Section 2.2.3.4), researchers have also deployed Semantic Web technologies in a wide range of applications in construction sector, including education, compliance checking, project management, facility management, and sustainability.

Education

E-learning is one of the most important applications of Semantic Web technology. Zhao adopted ontology and rules to represent domain knowledge of timber structure to support learning ancient Chinese architecture history (Zhang and Lu, 2012). Pathmeswaran and Ahmed (2009) developed a Semantic Web based mobile learning object repository. Ahmed et al. (2007) proposed a framework for e-learning metadata standards and ontology for sharable learning objects in construction management. Argüello et al. (2006) published a paper focusing on a Semantic Web portal using an ontology-based search engine.

Compliance checking

Construction industry constantly faces the problem of checking the compliance of products and processes to various regulations to ensure sound development and functioning of their services. Ontology, because of its advantage of knowledge modelling, is an appropriate approach to model the compliance requirement in building codes and regulations. Yurchyshyna concluded a preliminary conceptual framework based on Semantic Web technologies modelling the conformance checking problem, and presented an ontological method to semi-automatically check the conformity in construction (Yurchyshyna et al., 2010, Yurchyshyna and Zarli, 2009).

Pauwels et al. (2011b) presented an approach for a semantic rule checking environment for building design and construction. Bouzidi et al. (2012) enhanced the e-regulation of construction industry by establishing a domain-ontology where Semantics of Business Vocabulary and Business Rules and SPARQL are adopted to reformulate the regulatory requirements. Salama and El-Gohary (2011) proposed an approach applying semantic modelling to solve the problem of regulatory compliance checking in construction. Zhong et al. (2012) explored an ontology-based semantic modelling approach of regulation constraints focusing on construction quality inspection and evaluation domain. Zhang et al. (2015) proposed a construction safety ontology to formalise the safety management knowledge. Zhong et al. (2015) introduced an ontological approach to support the plan definition and compliance verification process of construction project.

Project management

Construction projects are information intensive. Quick information retrieval and correct information capturing an efficient information management is important to for construction project. Advance information technologies such as Semantic Web creates more benefits to facilitate management processes in the construction industry. Staub-French et al. (2003) developed an ontology to support construction cost estimating. Ruikar et al. (2007) discussed a Semantic Web based framework for shared definitions of terms, resources and relationships within a construction project. Lee et al. (2008) employed ontology in an intelligent decision support agent for CMMI project monitoring and control. Abanda et al. (2011a) proposed an ontological approach for house-building labour cost estimation. Tserng et al. (2009) proposed the ontology-based risk management (ORM) framework to enhance the risk management performance by improving the risk management workflow and knowledge reuse. Elghamrawy et al. (2009) presented a prototype of a semi-automatic framework based on OWL ontologies for storing and retrieving on-site construction problem information.

Facility management and smart home

Building facility management aims to capture static as well as dynamic information about how the building is running. Based on the information, human experts could make decisions to operate the facility in a more efficient way. Ontology provides a means to convert human knowledge to machine understandable format, which can support the decision-making process. Dibley et al. (2012, 2015) developed an ontology to deliver an intelligent multi-agent software framework (OntoFM) supporting real time building monitoring. Schevers et al. (2007) used IFC and Semantic Web technology for digital facility modelling of Sydney Opera house. Han et al. (2011) proposed a building energy management system based on ontology, inference rules, and simulation. Nemirovski et al. (2012) presented an ontology-based information system to capture the energy-related data throughout the whole building life cycle. Hu et al. (2011) examined a Semantic Web based policy interaction detection method with rules to model smart home services and policies with the aids of ontological analysis in the smart home domain, so as to construct a semantic context for inferring the interaction of policies.

Sustainability

The building sustainability is an emerging area of Semantic Web applications in construction domain. Garrido and Requena (2011) proposed an ontology for environmental impact assessment. Abanda et al. (2013a) developed an ontology for designing photovoltaic system. Edum-Forte and Price (2009) established a social ontology for appraising sustainability of construction projects. Kumazawa et al. (2009) used ontology engineering approach for knowledge structuring of sustainability science. Li et al. (2010) adopted information retrieval technique to develop low carbon ontology.

2.3.6.1 Critical analysis of Semantic Web applications

Based on the review of Semantic Web applications in construction sector, a critical review is undertaken. Several key findings are listed as follow:

1. A large number of Semantic Web applications emerged in recent year, which prove the validity of Semantic Web technologies in construction sector. Additionally, the feasibility of these applications have corroborated the shift of knowledge management in construction industry from human interpretation based approach to automated machine processing based approach.

2. Despite the large number of applications, most of ontology developments remain at conceptualisation of domain knowledge, establishment of high-level framework for domain ontology and development of lightweight ontologies. In general, heavyweight ontologies are able to offer more meanings than lightweight ontologies. The potentials of Semantic Web such as reasoning are not maximised in those applications.

3. The ontology developments and implementation in many of the applications requires the professional knowledge about ontology engineering and involvement of ontology experts or tools, which makes it difficult for building construction professions in practical use.

4. Very limit work has been done in terms of the building ontology for sustainable development as well as structural design domain, though sustainability issues are partially considered in some domain ontologies. According to the review conducted by (Grzybek, 2014), only 6 out of 105 Semantic Web applications in built-environment are concerned with sustainability, while only 2 are related to structural design.

The limitations of current applications in construction domain partially stem from the emerging nature of Semantic Web technology. However, the findings from review underpins the rationale of this research, which is to develop a Semantic Web application to model domain knowledge about sustainable structural design for facilitating the sustainable development in building structural design process.

2.4 Knowledge Management (KM) in construction industry

The past twenty years have seen increasingly rapid advances in the field of information and communication technologies (ICT). The advances have led to significant shifts in many business territories and industries towards more intelligent paradigms. The industries and academic institutes have shown keen interests of implement ICT in different domains. Under this circumstance, the Semantic Web has been increasingly recognised as a key technology to advance the ICT implementation. Among all the applications of Semantic Web, domain knowledge management has become one of the most important applications that draws attentions from the vast majority of Semantic Web pioneers in construction sector. This section briefly introduces the classification of knowledge in construction domain, current problems of knowledge management, and evolution of knowledge management in AEC.

Building construction is a knowledge intensive industry due to its unique features of work settings and virtual organisation (Rezgui, 2007a). The knowledge in construction domain could be classified as three types (Rezgui, 2001):

- Domain knowledge. This includes administrative information; for instance, zoning regulations, planning permission, standards, technical rules, product databases and so on. In principle, this information is available to all companies, and is partly stored in electronic databases.

- Organisational knowledge. This is company specific containing both formally in company records and informally through the skilled processes of the firm. It also comprises knowledge about the personal skills, project experience of the employees and cross-organisational knowledge.
- Project knowledge. This is both knowledge each company has about project and the knowledge that is created by the interaction between firms, including both project records and the recorded and unrecorded memory of processes, problems and solutions. It is not held in a form that promotes reuse, companies and partnerships are generally unable to capitalise on this potential for creating knowledge.

However, it is commonly accepted that the industry has been suffering from fragmentation that is somehow caused by poor communications among partners during a building project or between clients and suppliers of construction products. The knowledge management in construction domain is now regarded as a major challenge. The problems have been identified by Rezgui (2001):

- Much construction knowledge resides in the minds of the individuals working within the domain.
- The intent behind decisions is often not recorded or documented, which requires complex processes to track and record that comprise much project-related information.
- People responsible for collecting and archiving project data may not necessarily understand the specific needs of the actors who will use it.

- The data is usually not managed while it is created but is captured and archived at the end of the construction stage instead. People who have knowledge about the project are likely to have left for another project by this time - their input is not captured.

- Lessons learned are not well organised and are buried in details. It is difficult to compile and disseminate useful knowledge to other projects.

- Many companies maintain historical reports of their projects. It is difficult to reach the original report authors who understand the hidden meaning of historical project data. This historical data should include a rich representation of data context, so that it can be used with minimum (or no) consultation.

Over last two decades, research groups have continued to seek solutions to solve the problems by proposing more the initiatives and pushing them forward for better knowledge management in AEC sector. In 2010, Rezgui et al. provided a critical and evolutionary analysis of the ongoing research endeavours and projects related to KM (Knowledge Management) in the AEC industry, and indicated the future evolutionary trend of knowledge management in the field (Rezgui et al., 2010). In his paper, knowledge management in AEC industry can be described in terms of three generations where the Semantic Web, specifically the ontology underpins the second generation of knowledge management in AEC sector. The spectrum of three generations is illustrated using three axes in Figure 2.10. The vertical axis illustrates the evolution of management philosophies in the AEC sector. The horizontal axis demonstrates the evolution of ICT solutions in the sector. The third axis reflects the evolution of the impact of KM from individuals, organisations, to society.

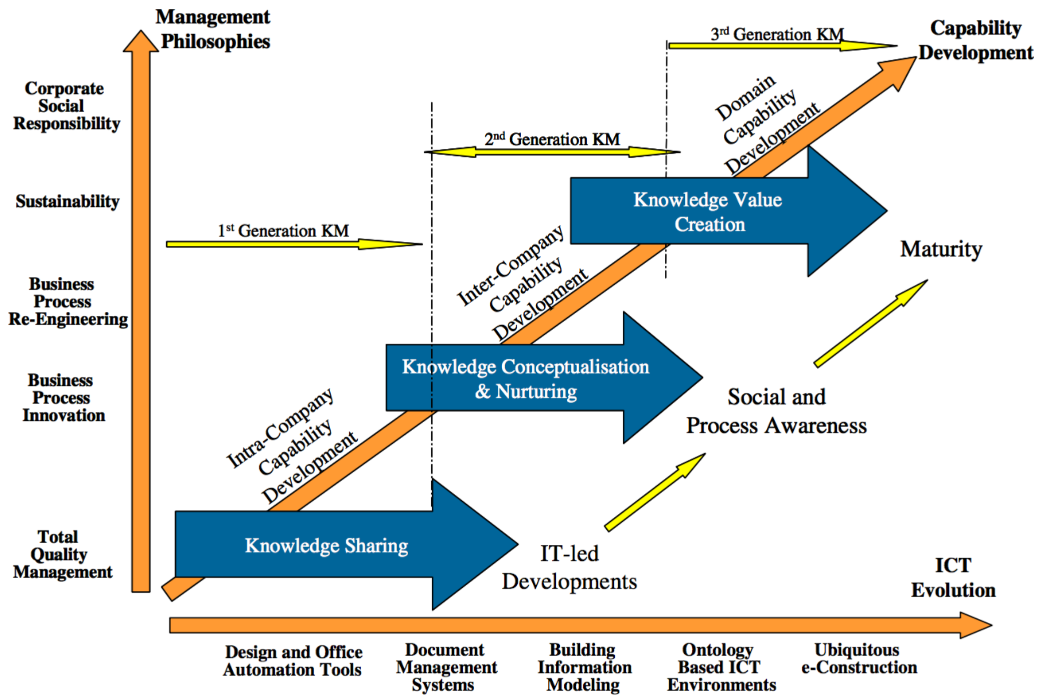


Figure 2.10 Generations of knowledge management in AEC (Rezgui et al. 2010)

KM in AEC Generation 1: knowledge sharing

In the first generation of knowledge management in AEC sector, knowledge sharing is document centred with implementation of proprietary or commercial electronic document management systems (EDMS). The knowledge contents of documents require human interpretation. Several key technologies are adopted in this generation to facilitate producing and spreading electronic documents, for example, office automation tools, computer aided drafting and then computer-aided design in architectural and engineering practices. Key words techniques from library science are widely used for archive and retrieval documents. Therefore, business process automation through IT within company becomes the main characteristic of the first generation of knowledge management in AEC sector.

KM in AEC Generation 2: knowledge conceptualisation and nurturing

The second generation of knowledge management in AEC aims at knowledge codification, and conceptualisation of buildings through product data modelling initiatives, such as STEP

(International Standards Organization, 1994), the IFCs (International Standards Organization, 2013), and consequently the introduction of Building Information Modelling (BIM) (Howard and Björk, 2008) in recent years. The emergence of Semantic Web, more specifically the ontologies, plays a key role in promotion of these initiatives (Rezgui et al., 2011). The content indexing, classification (clustering), and retrieval have considerably advanced knowledge management in the second generation. The focus of knowledge management has been shifted from intra-company to inter-company. As an important consequence, the integration of processes across disciplines becomes possible.

KM in AEC Generation 3: knowledge value creation

The third generation of knowledge management has been characterised by the emerging concern about environment and society. The aim is to deliver human and environmental friendly buildings and a sustainable built environment.

There is a large amount of efforts taken to facilitate this shift of knowledge management paradigms, for instance, data/product models developed by standardisation and/or industry consortia aiming at facilitating data and information exchange at software application level. Some well-known examples of these data model are STEP and IFC. Additionally, in order to facilitate communication and improve understanding between the various stakeholders involved in a project or across the product supply chain, other developments of dictionaries, thesauri, and several linguistic resources of construction terms have been driven at national level (Rezgui, 2007b). However, given the fact that the scope of AEC sector is vast, many software solutions still fall short of effective and efficient knowledge management. The shortcoming of current solutions promotes development of the Semantic Web applications for knowledge management in construction sector. Tasks to establish frameworks of structurally representing and reusing building related information and knowledge have been undertaken (Turk et al., 2005, El-Diraby, 2013, Anumba et al., 2008, Svetel and Pejanović, 2010).

2.5 Summary

This chapter has reviewed the sustainable development in construction industry with a focus on structural design domain. Structural engineers play an important role in sustainable building design in terms of reducing embodied energy and carbon. However, the contribution of structural engineer to current sustainable development is limited due to the fragmented information and inadequate tools in early design stage. This review establishes the need for developing an integrated system to manage the structural design knowledge and sustainability information.

Systems integration is all about interoperability. Section 2.2 begins with comparing the data interoperability and framework interoperability, then introducing the AEC/FM industry standards including IFC, gbXML and ifcOWL. These standards are developed to improve the interoperability between disciplines using various tools in a building project. Six system integration approaches are reviewed, including Distributed objects/ components, Software agents, Web-based systems, Web service and the Semantic Web, Ontology-based BIM system, and Hybrid integration approach. The Semantic Web approach offers great interoperability to handle both structural design knowledge and sustainability information, and therefore has been selected for the system development in this research.

This chapter has also explored the current web with identification of its limitations including lack of semantics, structured contents and ability of reasoning based on knowledge. Seeking solutions to overcome these limitations promotes the investigation of the Semantic Web technologies. The outcomes of the investigation including an overview the Semantic Web and ontology, and identification of Semantic Web technologies than can be used to model domain knowledge about sustainable structural design in this study. In order to justify the rationale of using Semantic Web technology in this study, it is imperative to review the current Semantic Web applications in building construction sector. A wide range of applications in construction area are examined, including knowledge management, education, project management, facility management, and sustainability. Through a critical analysis of the maturity level and applied areas, there are two main shortcoming of current applications. The first one is that most ontologies in building construction domain are lightweight ontologies focusing on the establishing structured representation of domain concepts without maximising the benefits of Semantic Web technologies for practical use such as rule-based reasoning. Secondly, very limited ontologies have been developed for sustainable design, especially the structural design domain. The analysis of current applications has formed a basis for this study, including the development of an ontology for modelling knowledge about the sustainable structural design and the implementation of this ontology in applications of concrete structural components design and selection. The methodologies used to develop this ontology are discussed in next chapter.

Chapter 3 Research Methodology

After literature review, this chapter moves on to introduce the research methodology and framework that are used to achieve the objectives proposed in Chapter 1. The contents of this chapter consist of five sections. Section 3.1 gives a brief overview on generic research methodologies. An exploratory research with prototype development and case study validation is adopted in this study as overarching research methodology. The justification of the research methodology selection is explained as well. Section 3.2 introduces CommonKADS that is adopted as knowledge engineering methodology in this work. In Section 3.3, important methodologies available in the literatures for ontology development are reviewed, and Ontology Development 101 is selected as the ontology development methodology in this work. Section 3.4 further proposes a methodological framework for this study, including methodologies, key tasks and tools to be used for ontology development.

3.1 Generic research methods

The meaning of doing research is a process of creating some new knowledge (Oates, 2006). This process involves a number of research tasks such as identifying a problem, gathering data, analysing data, interpreting the data and drawing conclusion from data. In terms of the

Computer-based system or product development, as demonstrated in this study, there are three main tasks required for such a research:

- Gather data about the computer-based product required using various methods such as interview, survey and document examination;
- Generate data (for example system model) to show whether the product works as initially intended;
- Test and evaluate the product by implementing case studies or user questionnaires.

Different strategies and data generation methods could be used to complete these three tasks during a research process.

3.1.1 Overview of relevant research methods

There are two major research methodologies for systematic investigation: quantitative research method and qualitative research method. Quantitative method provides summaries of data supporting generalisations about the phenomenon under study (Moskal et al., 2002). Qualitative method aims to understand more about human perspectives and provides a detailed description of a given event or phenomenon (Creswell, 1998). Bernard briefly compared the difference between quantitative and qualitative research methods (Bernard, 2002, Leydens et al., 2004). Despite the differences between the quantitative and qualitative approaches, there are some overlapping research methods required by both, such as literature review and data collection.

This study investigates how to use Semantic Web technology for sustainable structural design domain. In general, it is a Semantic Web application system which is a sub-type of information system research. A variety of research methods used in the information system area have been explored below.

3.1.1.1 Literature review

The thoroughness and critical analysis of literature review provide the foundation of research. In the early stage of research, literature review helps researchers in many aspects such as

- Understanding existing work in the chosen topic;
- Analysing the strength and weakness of previous work;
- Identifying the research gaps in the area;
- Choosing the appropriated theory or method that researcher will incorporated in the development;
- Finding evidence to support own work;
- And locating the place of research in current context.

The sources of literature review could be selected from a wide range of media, for example, books, journal articles, conference proceedings, reports, and government documents. Some of the literatures, considered to be more reliable or valuable than others, are categorised as primary literature sources. The primary sources include original documents, creative works and relics or artefacts, for example, a journal article reporting an original research finding. Meanwhile, unlike the primary sources, secondary sources are documents that used to interpret and analyse an event, person, topic, or primary sources, with at least one step removed from the event. Textbooks, newspapers, or review articles are common secondary sources.

In this study, both the primary and secondary sources are adopted. The findings from literature review have been presented in theoretical background parts of Chapter 2 and 3.

3.1.1.2 Developing research prototype

Prototype development is a typical research method that is widely used in information system (Baskerville and Wood-Harper, 1998). In the context of information system research, the theory/concept proposed usually leads to the development of a prototype system with the intention of illustrating the theoretical framework (Burstein and Gregor, 1999). The development of a prototype is also an appropriate method of evaluation at the early stages of a software development life cycle. It attempts to illustrate some or all of the proposed functionality of a system.

3.1.1.3 Case study

A case study explores complex real-life interactions as a composite whole (Yin, 2003). The strengths of case studies lie in the fact that they allow for covering a large amount of ground for an acceptable cost, and provide a means of looking in-depth at complex problems. In information system area, the case study method can be used to study the implementation efforts, the impact of system on organisations and society. As a popular research method, case study is particularly useful for validating developed prototype system.

3.1.2 Overarching research methodology adopted in this study

The selection of methods must be appropriate to the nature of the object studied and the purpose and expectations of inquiry (Sayer, 1992). This research aims to apply emerging technology in building construction sector. it is required to understand two domains: the sustainable structural design and the Semantic Web, and their relationships as well as underlying assumption.

The in-depth understanding of the two domains can be established by answering a group of questions: “What is sustainability?”, “What is the structural engineers’ role in sustainable development?”, “What methods can be used to improve sustainability?”, “What is the Semantic Web?”, and “What are the Semantic Web technologies?”.

The research question indicates the relationship between two object domains. This relationship could be represented using domain-implementation-technology as shown in Figure 3.1. The implementation process can be specified by answering questions such as “How domain knowledge about sustainable structural design can be managed in Semantic Web environment?”, and “In what scenario the Semantic Web could improve the sustainability of structural design?”. The use of technology can be specified by answer questions such as: “What Semantic Web technologies can be used?”, “What software can be used for implementation?”, and “How can information in Semantic Web environment be easily accessed?”.

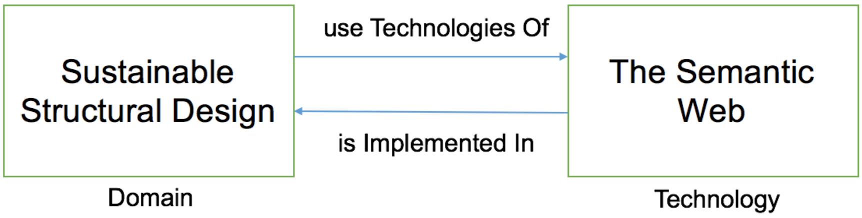


Figure 3.1 Semantic relationship between two domains.

An assumption implied by the research question is that the knowledge about sustainable structural design could be managed in semantic environment. The assumption can be justified by answering the questions “What is the current gaps of sustainable structural design?” and “What can the Semantic Web do to bridge the gap?”.

The understanding of the research question forms the basis of selecting appropriated research methodology for this study. Therefore, based on the analysis of research domains, relationship and assumption, an exploratory qualitative study with prototype development and case study based evaluation approach is adopted in this study.

The exploratory research is considered as an appropriated method for emerging and evolving domains such as information system. It provides a comprehensive insight into an issue or situation. This is the reason that exploratory research is often adopted qualitatively study. The outcome of the exploratory research is primary finding that determines the subsequent research methods and activities.

To support the findings from exploratory study, evidence should be formulated based on the convincing argument, a justification from data analysis, and a proof-by-demonstration. In information system, prototype can be used as evidence to support this claim (Pan, 2006).

The case study is a widely adopted evaluation approach for the development of prototype system. using case study can facilitate understanding of reality and help testing theory and data (Yin, 2003). It is often recommended to use real-world case or data to evaluate the prototype (Sommerville, 2000).

3.1.3 Justification of the methodology selection

The Semantic Web domain is relatively new and currently under fast development. There is no existing mature system or approach that can be directly adopted in this study. Therefore, the exploratory study is suitable for establishment of a thorough review of literatures and interview with experts to gather knowledge about the emerging Semantic Web technology. The “what” questions raising from research question such as “What is the Semantic Web?” and “What are the Semantic Web technologies?” could be answered during the exploratory study. Moreover, the questions “What is the current gaps of sustainable structural design?” and “What can the Semantic Web do to bridge the gap?” could be answered by reviewing sustainable development in construction sector and identifying the current research gaps of sustainable structural design through exploratory study.

The exploratory study is suitable for identification of Semantic Web technologies, engineering methodologies and tools that can be used to model domain knowledge. The “how” questions such as “How domain knowledge about sustainable structural design can be managed in Semantic Web environment?” and “what” questions such as “What Semantic Web technologies can be used?” can be answered based on the findings from exploratory study. For example, the OWL ontology is selected to model the knowledge concepts and relationships in sustainable structural design domain; while the SWRL is selected as the rule language to model the structural design criteria and sustainable rules.

The rationale of assumption in research question that using Semantic Web in sustainable structural design domain can be supported by the review of current applications of Semantic Web technologies in construction sector. By analysing the applications, the advantages of implementing Semantic Web technologies in construction domain are specified and the shortcomings of existing applications are also identified. For example, ifcOWL ontology is determined as a reusable semantic resource for this study.

To prove the applicability of Semantic Web in sustainable structural design domain, developing a prototype application with case study evaluation is a suitable approach. The questions “What software can be used for implementation?”, and “How can information in Semantic Web environment be easily accessed?” can be answered by the demonstration of different applications in case study.

3.2 Knowledge engineering methodologies

Developing ontology for a knowledge-based system is a process of knowledge engineering. To introduce the concept of knowledge engineering, it is important to clarify what knowledge is and distinguish its associated terms, for example the relationships and differences between knowledge, information and data. In addition, this could facilitate the understanding of the context of this research and the main trend of evolution regarding to the knowledge management in architecture, engineering and construction industry.

3.2.1 Data, information and knowledge

Although sometimes it is difficult to draw clear lines between data, information and knowledge, researchers have put many efforts to distinguish these three concepts.

- Data - Data are regarded as unorganised and unprocessed facts (Du and Liu, 2011). They are a set of structured discrete facts that statically record an event, which are prerequisite that constitute information (STREDÁKOVÁ, 2007).

- Information - Information is an aggregation of data that facilitate the process and improve the quality of decision making. It can be defined as reformatted and processed data. Unlike data only representing quantity, information also recognises the relationships between data in a specific context describing a fact. In other words, information has meanings, purpose and relevance (STREDÁKOVÁ, 2007). Therefore, information is distinguished from data by emphasising quality.

- Knowledge - Knowledge is a collection of organised information after cognitive processing and validation (Cooper, 2014). It is information enhanced by the details about how it should be used or applied, which can be used for the purpose of problem solving.

As shown in Figure 3.2, data, information and knowledge are often represented in hierarchy from the lower level of data, to the higher level of wisdom, which is well known as the DIKW (Data, Information, Knowledge and Wisdom) pyramid (Rowley, 2007).

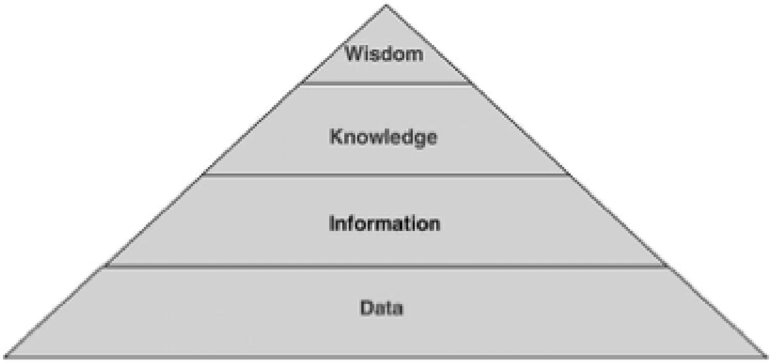


Figure 3.2 DIKW (Data, Information, Knowledge and Wisdom) pyramid (Rowley 2007).

3.2.2 Knowledge engineering

Knowledge engineering is the process of constructing knowledge-based system. It involves the analysis of developing and maintaining process of the system and the corresponding methodologies, tools and languages applied in this process (Studer et al., 1998). In computer science, knowledge-based system (KBS) is an artificial intelligence technique, which is a computer program built for solving problem using knowledge base. The understanding of knowledge engineering is evolving with its development, shifting the paradigm from “a transfer approach” to “modelling approach”.

In the early 1980s, the knowledge engineering was concerned with transferring human knowledge into a knowledge base on computer. The human knowledge was often collected by interviewing the experts on specific areas, and implemented in the form of rules which can be executed by rule interpreter. However, the limitations of this transfer approach were posted out. Firstly, the simple representation of rules lacked capability of representing different types of knowledge, which means it is not feasible to produce and maintain large mixture type of knowledge bases. Therefore, the application of transfer approach was limited to small scale knowledge system. Secondly, the knowledge acquisition of this transfer approach was collecting the already existing knowledge, which was found to be inadequate. Because it neglected the importance of human’s tacit knowledge in problem solving process. These shortcomings promoted the shifting to the modelling approach.

Nowadays, a commonly held view is that knowledge engineering can be seen as a modelling activity (Schreiber et al., 1994). Rather than transferring human knowledge into an appropriate computer representation, it is intended to create a model to solve problem by offering similar results as human domain experts do. In this model construction process, not only the existing knowledge, but also the hidden parts of the knowledge that human experts may not consciously articulate, are collected and structured in the knowledge acquisition process of this modelling approach.

By far, various knowledge engineering approaches have been proposed and developed with different emphasis, such as CommonKADS, MIKE, and PROTEGE-II.

3.2.3 CommonKADS methodology

The CommonKADS methodology has been adopted in this study, because (1) it is the leading standards for knowledge analysis and knowledge intensive system development (Schreiber, 2000); (2) although CommonKADS is not a ontology engineering methodology, it covers some essential aspects from knowledge management and analysis to knowledge-intensive information system development (Sure et al., 2009). It has a focus on the initial phases for developing knowledge management applications, which is suitable for the early knowledge acquisition stage for formal ontology development.

Detailed investigation of CommonKADS methodology by Schreiber (2000) classified the knowledge model construction process into three stages which involves key activities to complete. The three main stages are knowledge identification, knowledge specification, and knowledge refinement. In addition to specify the techniques applied in the activities of each stage, the CommonKADS methodology gives a guideline on how to implement it in knowledge model construction. It should be noticed that modelling process is typically a constructive activity that deviations and variations from the guideline are often allowed and required, depending on the particular application that the knowledge model is built for.

Knowledge identification

The first phase of CommonKADS methodology is knowledge identification. Information sources that are useful for knowledge modelling are identified. This is a preparation phase for the actual knowledge model specification. A lexicon or glossary of domain terms is constructed. Existing model components such as task templates and domain schemas are surveyed, and components that could be reused are made available to the project. Typically, the description of knowledge items in the organisation model and the characterisation of the application task in the task model form the starting point for knowledge identification.

Key activities:

- Domain familiarisation. Explore and structure the information sources for the task, as identified in the knowledge item listings. During this process, create a lexicon or glossary of terms for the domain.

- List potential model components. Study the nature of the task in more detail, and check or revise the task type. List all potential reusable knowledge-model components for this application.

Knowledge Specification

In the second stage, the knowledge engineer constructs a specification of the knowledge model. First, a task template is chosen and an initial domain schema is constructed, using the list of reusable model components identified in the previous stage. Then the knowledge engineer will enrich the knowledge model. There are two approaches to complete the knowledge model specification, namely starting with the inference knowledge and then moving to related domain and task knowledge, or starting with domain and task knowledge and linking these through inferences. The choice of approach depends on the quality and detailedness of the chosen task template. In terms of the domain knowledge, the emphasis in this stage is on the domain schema rather than the knowledge base.

Key activities:

- Choose task template.

- Construct initial domain schema

- Complete specification of the knowledge model. There are basically two routes: middle-out and middle-in for completing the knowledge model once a task template has been chosen and an initial domain schema has been constructed.

Knowledge Refinement

In the final stage, attempts are made to validate the knowledge model as much as possible and to complete the knowledge bases by inserting a more or less complete set of knowledge instances. An important technique for validating the initial specification that comes out of the previous stage is to construct a simulation of the scenarios gathered during knowledge identification. Such a simulation can either be paper-based or involve the construction of a small, dedicated prototype. The results of the simulation should give an indication whether the knowledge model can generate the problem-solving behaviour required. Only if validation delivers positive results is useful to spend time on completing the knowledge bases.

Key activities:

- Validate Knowledge Model
- Complete Knowledge Bases

Usually, these three stages are intertwined and iterative processes are required for single or multiple stages as shown in Figure 3.3 (Schreiber, 2000).

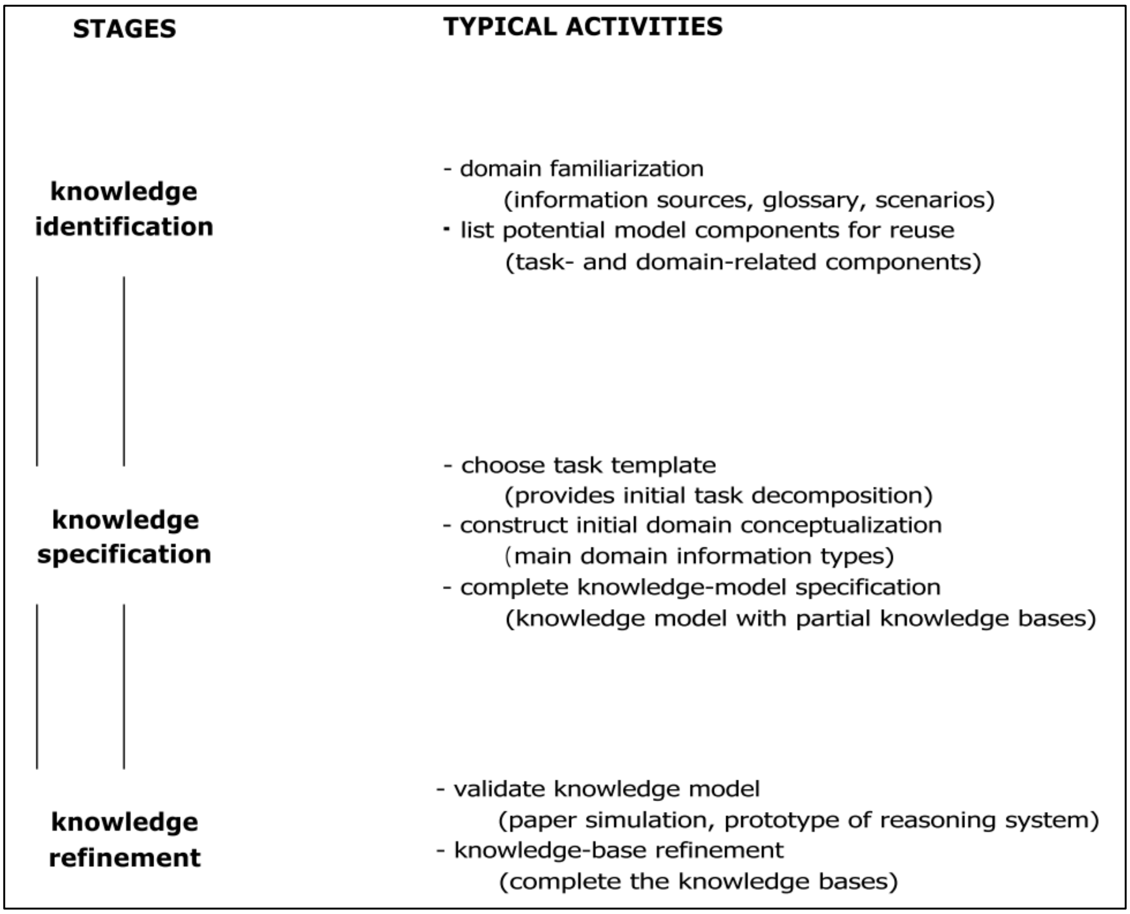


Figure 3.3 CommonKADS methodology.

3.3 Ontology development methodologies

Given the fact that ontology development is a subtask of knowledge engineering that have been review in Section 3.2, ontology engineering is further explained as a successor of knowledge engineering in this section.

Ontology engineering is a research methodology which supports the design rationale of a knowledge base, kernel conceptualisation of the world of interest, semantic constraints of concepts together with sophisticated theories and technologies enabling accumulation of knowledge which is dispensable for knowledge processing in real world (Mizoguchi, 2003). Before choosing the appropriate ontology engineering methodology for OntoSCS ontology development, the review of current methodologies is a substantial part of this study. Prior to starting the development of an ontology, several critical questions always need to be answered by the ontology engineers (Corcho et al., 2003):

- Which methodologies can I use for building ontologies?
- Which tools support to the ontology development process?
- Which language should I use to implement my ontology?

The answers to these questions are various, which are the inspiration and origin of a series of methodologies for ontology development. Due to the fact that the domain of ontology methodologies is vast, specification of these methodologies is beyond the scope of this study. However, a general review will be given in this section. Based on a comparison of the strengths and weakness of each methodology, Ontology Development 101 methodology is selected for this study and applied in a prototypical system development.

3.3.1 Current methodologies for ontology development

In early 1990s, the first general steps for Cyc development were proposed by Lenat and Guha (1989). 5 years later, Uschold and King (1995) introduced a methodology on the basis of their experience in building the Enterprise ontology. At the same year, Gruninger and Fox (1995) developed another enterprise ontology named the TOVE (TOronto Virtual Enterprise) project ontology. An outline of the methodology used in TOVE project was the proposed and refined in 1996. At the 12th European Conference for Artificial Intelligence (ECAI’96), Bernaras et al. (1996) introduced a methodology that was used for an electrical networks ontology development as a constitute of the Esprit KACTUS project. In the same year, Gómez-Pérez et al. described the Methontology method and updated in later publications (Gómez-Pérez et al., 1996). In 1997, Swartout et al. (1997) presented a methodology for constructing SENSUS ontology. At the beginning of 2000s, On-To-Knowledge methodology was proposed by Staab et al. (2001) as an outcome of project with the same name. The Ontology Development 101 methodology (Noy and McGuinness, 2001) appeared at the same year providing a practical guide for domain ontology development. Since the ontology development methodologies have been comprehensively reviewed in many publications (Fernández-López and Gómez-Pérez, 2002, Corcho et al., 2003), this section briefly introduces the important methodologies and key steps.

Uschold and King

This methodology is based on the experience of developing the Enterprise Ontology, an ontology for enterprise modelling processes at the Artificial Intelligence Applications Institute (AIAI) of Edinburgh. The steps proposed by the methodology are given below.

1. Identifying purpose, which clarifies the purpose and applications of building the ontology;
2. Building the ontology, which contains three steps: ontology capture, coding, integrating existing ontologies;
3. Evaluation, which makes a technical judgement of the ontologies, associated software environment, and documentation according to requirements specifications, competency questions, and/or the real world;
4. Documentation, which suggests guidelines for documenting ontologies, according to the type and purpose of the ontology.

Drawbacks:

1. Conceptual modelling process is missing between the knowledge acquisition and ontology implementation (Gómez-Pérez et al., 2004);
2. A lack of techniques for carry out the activities of the methodology (Pan, 2006).

Methodology of Grüninger and Fox

This methodology is based on the experience in the development of the TOVE project ontology within the domain of business processes and activities modelling. The major steps proposed by this methodology are as follows:

1. Capture of motivating scenarios;
2. Formulation of informal competency questions;
3. Specification of the terminology of the ontology within a formal language;
4. Formulation of formal competency questions using the terminology of the ontology;
5. Specification of axioms and definitions for the terms in the ontology within the formal language;
6. Establish conditions for characterising the completeness of the ontology.

Drawbacks:

1. As a first-order logic based formal method, it focuses on transforming informal scenarios expressed in natural language into a computable model expressed in logic. However, it lacks detailed guide and technique to support undertaking the activities in this methodology. Therefore, it has not been adopted in this study.

METHONTOLOGY

The METHONTOLOGY framework (Fernández-López et al., 1997, López et al., 1999) enables the construction of ontologies at the knowledge level. The ontology development process refers to several groups of activities performed when building the ontology. Activities can be classified into three groups:

1. Ontology management activities: scheduling, control and quality assurance;

2. Ontology development-oriented activities include specification, conceptualisation, formalisation and implementation;

3. Ontology support activities: knowledge acquisition, evaluation, integration, documentation, and configuration management.

Drawbacks:

1. It adopts a middle-out strategy for identifying concepts, which means the most relevant concepts are firstly identified.

2. Techniques for the control activity remain to be specified.

3. Additionally, the direct formalisation of the conceptual model in this methodology is challenging for beginners (Pan, 2006). Based on these reasons, this methodology is not adopted.

The KACTUS

This methodology was developed as a part of Esprit KACTUS project. It is conditioned by application development. Therefore, the developed ontology representing application knowledge needs to be refined once new application is built. In this methodology, following steps are taken: specification of the application, preliminary ontology design based on relevant top-level ontological categories, ontology refinement and structuring.

Drawbacks:

1. The heuristics are too general without detailed steps to support the ontology development.

Ontology Development 101

Ontology Development 101 is a guide proposed by Noy and MacGuiness for the beginners to create their first ontology. This method emerged based on the experiences with the development of Protégé 2000, Ontolingua and Chimaera tools. This guide covers all the phases of ontology development including defining classes in the ontology, arranging classes in a taxonomic hierarchy, defining slot and describe allowed values for these slots, and lastly filling in the values for the slot (Breitman et al., 2007). Some complex issues related to defining class, property and instance are discussed. The process described in the guide is naturally iterative and based on some fundamental rules assisting in making design decisions during ontology development (Iqbal et al., 2013). Interaction and refinements by domain experts and analysts are important in this development process with regard to validating the ontology and retrofitting new knowledge into ontology. As shown in Figure 3.4, there are seven major steps in this methodology (Breitman et al., 2007):

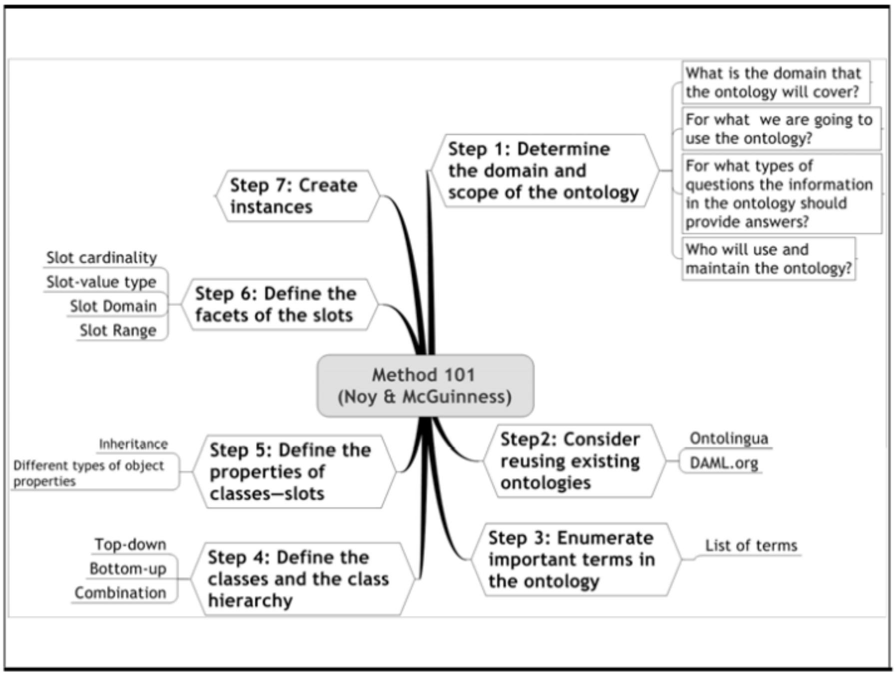


Figure 3.4 Ontology Development 101 methodology.

1. Determine the domain and scope of the ontology.

As building an ontology is a process of creating a model of a particular domain for a purpose, the scope of ontology has to be defined according to the application of ontology. To determine the domain and scope of ontology, competency questions are introduced as an ontology development technique. In this methodology, the development of an ontology starts by providing answers to the competency questions. By answering these questions, the ontology engineers could determine what concepts should be included in the ontology and what should be eliminated. Some examples are given here:

- What is the domain that the ontology will cover?
- What is the ontology going to be used for?
- For what types of questions should the ontology provide answer?

- Who will use and maintain the ontology?

It is worth noting that the competency questions are also useful at the final stage of development to evaluate the ontology (Gruninger and Fox, 1995).

2. Consider resuming existing ontologies

It is always a good practice to consider if the terms in this ontology have been implemented in other ontologies, or if it is possible to refine, extend or use the entirety of existing ontology to serve this one. In some case that the ontology is to build for interaction with other existing ontologies, the reuse becomes a prerequisite.

3. Enumerate important terms in the ontology

The main task of this step is creating an unstructured list of all the relevant terms in the targeting domain of proposed ontology. Traditional elicitation techniques are useful when making the list, for example, interviews, dynamic document reading and requirements workshops.

4. Define classes and class hierarchy

The terms identified in step 3 are organised in a taxonomic hierarchy. There are three approaches to define the class hierarchy.

- The Top-Down Approach: this approach is also known as functional decomposition. The general classes are firstly defined the decomposed into more specialised classes.

- The bottom-up Approach: the most specific classes in this approach are first defined, then generalised to groups. A more generic class is chosen as superclass for each group of more specific classes. This approach starts with listing all the classes before deciding on its organisation.

- The Mixed Approach: this approach combines the above two approaches. First identified classes are the more salient ones that are expected to be included in the ontology. Then the decomposition/generalisation processes are successively applied to the initially defined classes.

Although it is still debatable that which approach should be adopted (Uschold and Gruninger, 1996), all the approaches should follow the principle that the finished taxonomic hierarchy is consistent. In other words, if a class A is the superclass of a class B, then every instances of B is also an instance of A.

5. Define class properties (or slot)

The classes alone are not sufficient to contain enough information to answer the competency questions asked in step 1. In order to provide necessary semantic to define the domain and fully use the ontology, properties are defined in addition to the classes. Although, the existence of properties is independent from classes, it is a necessary part of ontology to attain the purpose of development. There are mainly three types of property in ontology: the object property that defines the relationship between classes or instances; data-type property that defines the relationship between instance and data-type values; and the annotation property that provides a piece of information for comments of concepts in ontology. A subclass inherits all the properties of its superclass.

6. Define the facets of the properties

   Facets mean the values and number of values that properties have. The values of properties can be constrained by cardinality (the number of the values) and value type. Some ontologies allow single or multiple values to be assigned to properties, such as OWL ontology.

7. Create instances

   This is the last step of this methodology, which consists of three tasks: (1) choosing a class; (2) creating an individual instance of the class, and (3) filling in the property values.

3.3.2 Justification

The adoption of Ontology Development 101 methodology for this study is based on the following reasons:

- Easy to use. The Ontology Development 101 is an ontology engineering methodology designed for beginners with no former experience of ontology development.
- Specification of detailed steps. The methodology explicitly explains the procedure of developing an ontology from scratch.
- Integration with tool. The methodology provides a guidance of how to implement the ontology step-by-step in Protégé software environment.
- Consideration of reusing existing semantic resource. Since the ontology developed in this study adopts the concepts from ifcOWL ontology, this methodology is suitable for development from reuse of existing ontologies.

3.4 The overall methodological framework

The development of an ontology-based decision support system is a combination of three main areas of Artificial Intelligence and Semantic Web: knowledge engineering, ontology engineering and software engineering. The development of an ontology in a knowledge-based system is a sub-task of knowledge engineering. Through the development of ontology, software is required for facilitating the process. In this study, CommonKADS and Ontology Development 101 are chosen as methodologies for knowledge and ontology engineering respectively. CommonKADS provides a framework for knowledge acquisition for the problem domain. Ontology Development 101 is the core of the ontology development and implementation. The proposed methodological framework (Figure 3.5) illustrates the relationship between the methodologies and tools adopted in OntoSCS system development process.

3.5 Summary

This chapter has established the research methodology for this study. Exploratory study with prototype development and case study evaluation is the primary research methodology adopted for this research. The exploratory study provides theory foundations for the prototype development, while the results from prototype system will support the findings obtained from exploratory study. To develop the ontology-based prototype system, which is essentially a knowledge-based system, CommonKADS and Ontology Development 101 are selected as knowledge engineering and ontology development methodologies. A methodological framework with key techniques and tools has been established. In the ensuing Chapter 4 and Chapter 5, design and implementation of prototypical system are examined respectively.

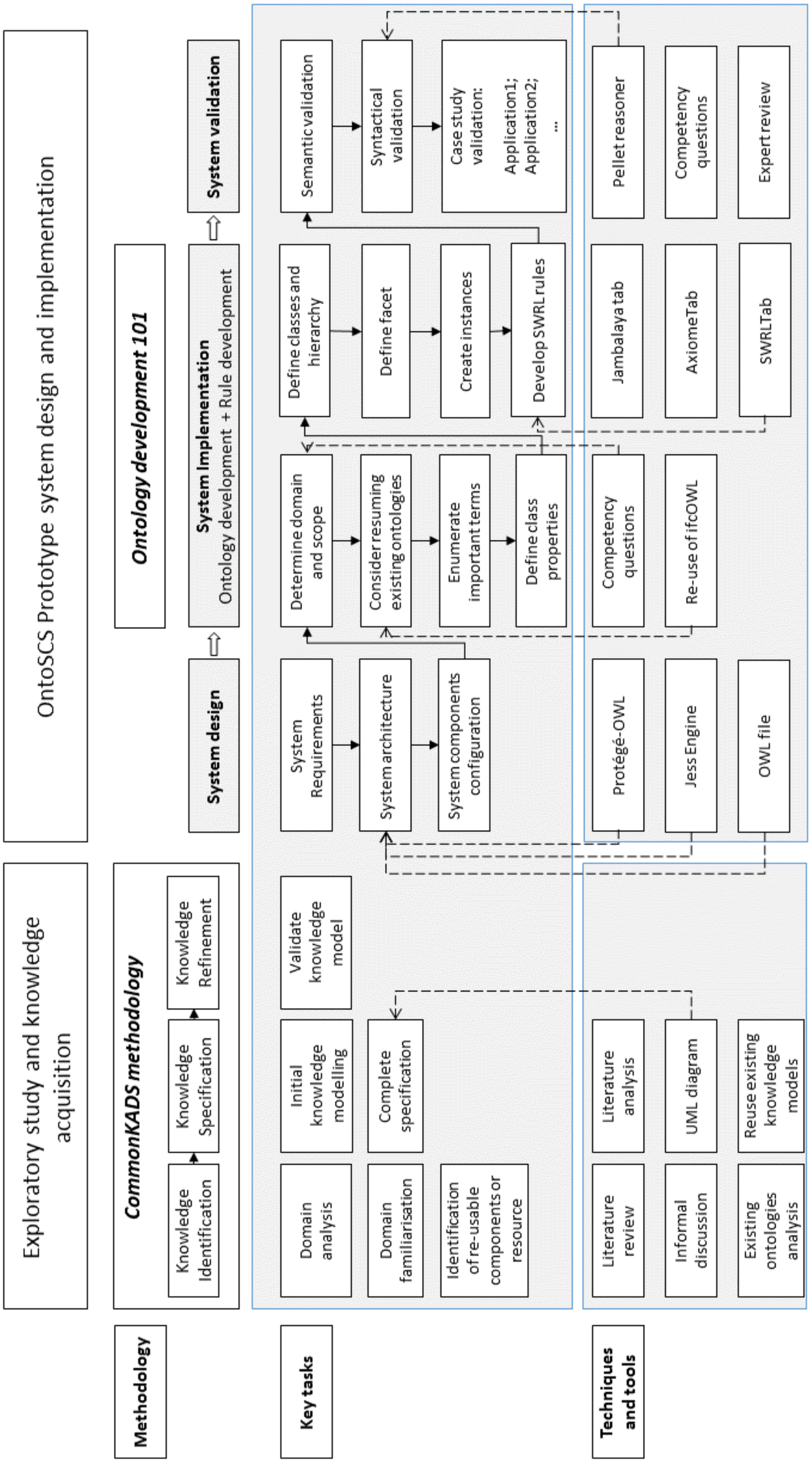


Figure 3.5 Framework of methodologies adopted in this research.

Chapter 4 System Design

This chapter starts with specifying the key requirements for developing an ontology knowledge-based system in Section 4.1. The system architecture is therefore devised in Section 4.2 to realise an ontology application OntoSCS for the use of sustainable concrete structural design.

4.1 System development requirements

As an indispensable task of developing knowledge-based system, the specification of system requirements determines the function, overall performance and further extensibility of this system. Therefore, prior to introducing the system design, the system development requirements have been concluded as follows:

- A central knowledge base in the form of ontology should be established. All the objects that define the sustainable structural design domain can be clearly identified and captured. In addition, the relationships between the objects should be organised using appropriate hierarchy and properties in this knowledge base;

- The ontology should use as much as possible of existing semantic resource in the building design domain to achieve maximum capability of sharing and exchanging knowledge between different domains;

- The knowledge and information of given domain should be represented concisely, rapidly retrieved and effortlessly maintained;

- To allow anyone to further exploit this system, the development of this OntoSCS system should be based on open source platform. Additionally, the output of this research should be free to access and in a neutral form that other researchers could adopt for different utilisations or ontology engineering (new ontology creation, ontology alignment, and ontology merging, etc.) with minimal redesign.

- The development of system in recommended to comply with the principles of agile engineering, which requires adaptive planning, evolutionary development, early delivery, continuous improvement, and encourages rapid and flexible response to change;

- Reasoning function needs to be supported in this system, in order to represent the structural design criteria and sustainability requirements;

- It is not necessary that the ontology should be initially comprehensive and exhaustive. The core outcome of this study is a practical ontology development for structural engineer. Hence, the OntoSCS ontology can be built on core concepts of sustainable structural design domain in the first place, and then enhanced incrementally by adding more objects from related domains.

On identifying these requirements of system development, the strategies used to build OntoSCS have been determined and wrapped up to fulfil the requirements summarised above respectively:

- Firstly, ontology is selected as the knowledge model for the system. Different from data or object oriented modelling, the ontology could explicitly capture domain knowledge by specifying the concepts and organise the relationships in a formal structure without constraints. Since the syntax of ontology is essentially based on Extensible Markup Language (XML), the presentation is relatively intuitive and straightforward for both ontology engineer and domain expert to understand and use.
- Secondly, OWL DL language is adopted as the primary ontology language to build OntoSCS system by the reason of its expressiveness and reasoning.
- Lastly, in terms of system development platform, the Protégé-OWL is used. Protégé-OWL is written in Java programming language which enables implementation over different machines and operating systems.

4.2 System architecture

4.2.1 Generic N-tier architecture for Semantic Web applications

Like other information systems, the Semantic Web based system is designed around several essential layers in conceptual level: presentation, application logic and resource management. In practice, there is a number of ways to combine or distribute these layers, in which case the layers are referred as tiers. In recent years, the N-tier architecture has shown its advantages in designing information system by incorporating the web services. Figure 4.1 illustrates a generic

N-tier architecture of web based information system (Alonso, 2004). The N-tier architecture consists of several main components: client or web browser, the presentation tier, the application logic tier and database tier. The presentation tier is used to handle all the visible operations between client and browser, accepting input from end-user and displaying results as output through the direct communication with the application tier. Recent development of this tier is Semantic Web browser that enables browsing ontologies on the web. The application tier plays as a control centre that connects to the databases and processes data before delivering the results to the presentation tier. The database tier is where the data is stored and managed. In the Semantic Web application, ontology model is located as single file or database server in this tier.

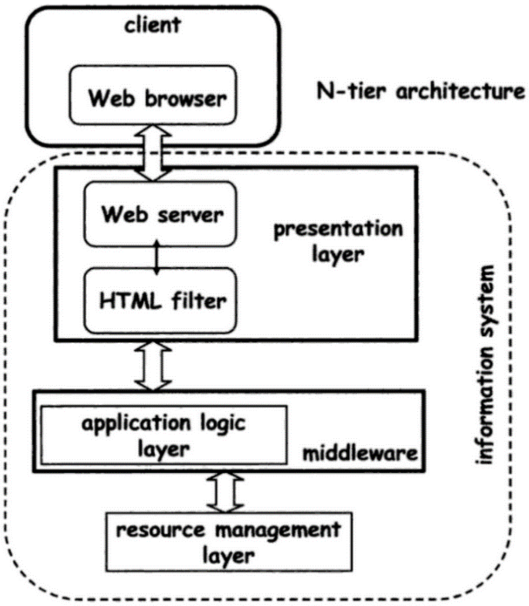


Figure 4.1 N-tier architecture of information system (Alonso 2003).

Abanda (2011) demonstrates a further interpretation of the N-tier architecture applied in Semantic Web applications. As shown in Figure 4.2, this architecture incorporates Protégé-OWL API and SWRL API in application logic tier, to access the OWL ontology model stored in database tier. Either OWL file or ontology server can be selected as storage format for ontology model.

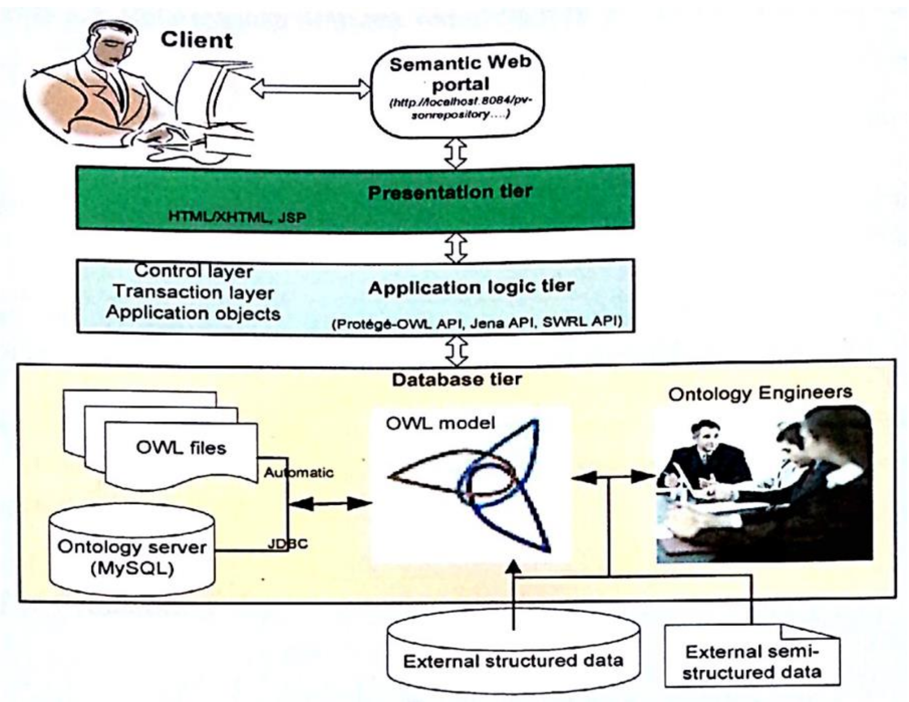


Figure 4.2 N-tier architecture of Semantic Web application (Abanda 2011).

Because of the advantages of N-tier architecture such as adaptability, encapsulation, re-use and quality, it has become a standard for Semantic Web applications. In this study, only application logic tier and database tier will be developed due to the limited scope of the study. It is possible to develop presentation tier and client in future work. In order to realise the N-tier architecture in real system development, it is imperative to determine the essential components that construct the system. The next section will explain the system configuration and key components to construct the Semantic Web application OntoSCS.

4.2.2 System architecture of OntoSCS

The OntoSCS system consists of three core parts: knowledge base (database tier), inference rule engine and ontology management system (application logic tier). They will be explained in details respectively in following sections.

Knowledge base

The OntoSCS system developed for assisting decision-making in structural design is essentially a knowledge-based system (KBS) that employs Semantic Web technologies to manage structured knowledge about building structural design and associated information about sustainability. Different from the conventional computer program processing data via code and algorithm, knowledge-based system represents human knowledge in an explicit way such as ontologies and/or rules. Through reasoning the knowledge stored in the system, the system is able to emulate or aid human expert to solve complex problems. Typical knowledge-based systems consist of two sub-systems: knowledge base and inference engine. The knowledge base is a repository of the expert knowledge that is useful to solve problems in the task domain. It contains two representation forms of domain knowledge: facts and rules. Facts represent the fact about the world such as “steel melts at temperature 1375 °C”, which are often organised as structured data in an object model using class, subclass and instance. On the other hand, the knowledge base also includes a set of condition (if-then) rules to express logic deduction of human knowledge. For example, if the steel structure is exposed to fire with temperature higher than 1375 °C, then it will be melted. In different knowledge-based systems, the facts and rules are stored in various forms of knowledge base. Figure 4.3 illustrates a knowledge-based system structure in which facts and rules are kept separately in knowledge base and database respectively.

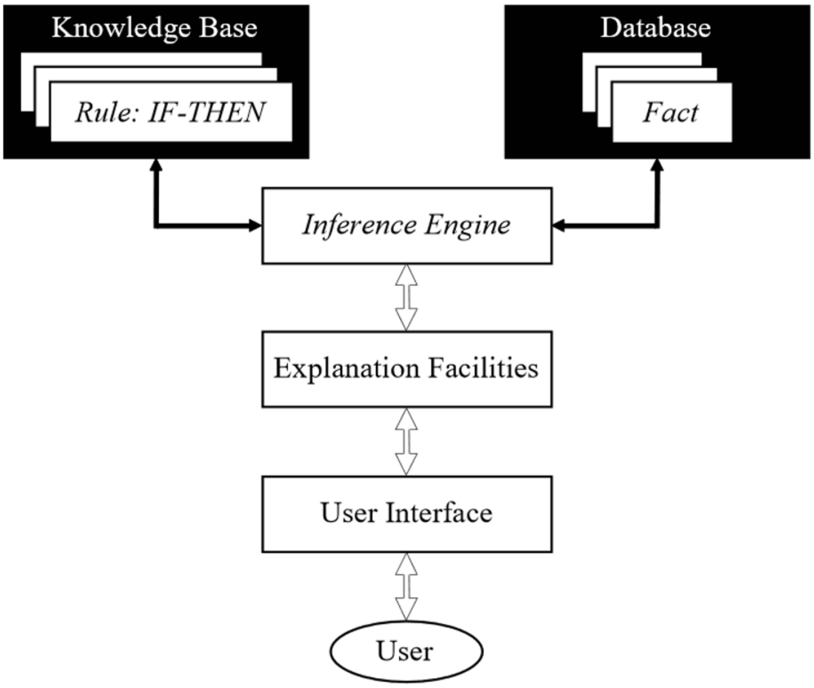
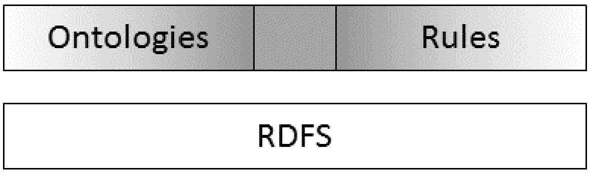
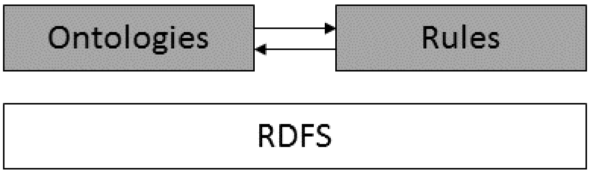


Figure 4.3 Knowledge-based system structure.

In recent years, ontologies are recommended to build knowledge base of KBS to represent the facts of domain knowledge in a formal structure. In addition to ontology, semantic rules languages are exploited to represent the rule part of knowledge. However, there is a fundamental issue in Semantic Web, which is the integration of different layers of its conceived architecture (Eiter et al., 2006). 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. In a homogeneous approach both ontologies and rules are embedded in a logical language L without making a priori distinction between the rule predicates and the ontology ones. To reason, a unique inference engine of L is to be used (Esposito, 2007). In a hybrid approach there is a strict separation between rule predicates and ontology ones. Reasoning is done by interfacing existing rule engines with existing ontology reasoners. The difference of two integration approaches is shown in Figure 4.4.



(a) Homogeneous approach



(b) Hybrid approach

Figure 4.4 Homogeneous and hybrid approaches.

The homogeneous approach is adopted in this study for three reasons. Firstly, SWRL is the selected rule language as an extension of OWL DL for more flexible inference beyond classification capability, such as mathematical relationships and logic rules. Secondly, this approach provides seamless and homogeneous semantic integration of ontology and rules. Thus, the SWRL rules can be store in the OWL ontology as single file, which is convenient to manage and migrate. Finally, the two-layer structure of combination offers an efficient way of updating and extending the ontology-based system without conflicts between ontology and rules. On one hand, the OWL ontology provides an open world to construct terminological part of knowledge and represent structured knowledge by class hierarchy and properties; on the other hand, the SWRL rules deal with the regulatory principles in the domain knowledge by inference function. In summary, the integration structure of OWL ontology and SWRL rule set in OntoSCS system knowledge base is demonstrated in Figure 4.5.

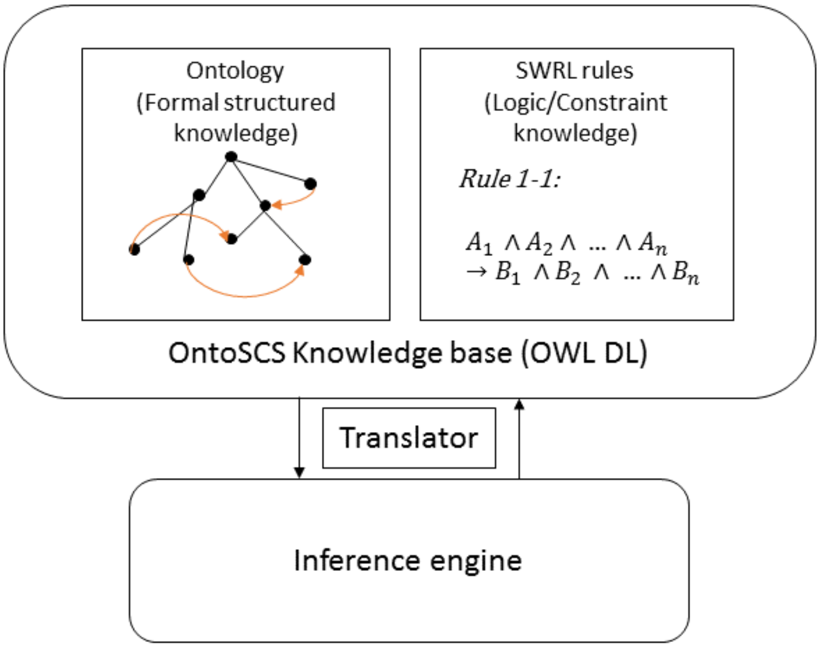


Figure 4.5 The structure of knowledge base in OntoSCS system.

As shown in Figure 4.5, ontology model and SWRL rules are integrated in a unified format OWL DL in the OntoSCS knowledge base. In this knowledge base, the facts of problem domain are captured as formal structured knowledge in ontology model; more specifically, in OWL DL format. Class, subclass, property and instance are used to represent the concepts and relationships between concepts in knowledge domain. The following examples illustrate how these concepts and relationships are represented as OWL DL language.

Classes

The objects of problem domain; for example, *"Concrete"* and *"Steel"* in the structural design domain are represented as classes in OWL DL:

```
<owl:Class rdf:ID="Concrete">
<owl:Class rdf:ID="Steel">
```

Hierarchy of classes

The hierarchy of classes and subclasses in ontology is represented using *“subClassOf”* in OWL DL. For example, the class *“BuildingElements”* involves a group of structural components in building system: *Beam, Column, Slab and Roof.* These structural components are organised as subclasses of the *“BuildingElement”* class. One of the subclass, *“Column”* contains three types that are *“SquareColumn”, “RecColumn”* and *“RoundColumn”* respectively. This three levels hierarchy is encoded in the form OWL DL as following:

```
<owl:Class rdf:ID="Column">
    <rdfs:subClassOf>
      <owl:Class rdf:about="#BuildingElement"/>
    </rdfs:subClassOf>
  </owl:Class>
…
<owl:Class rdf:ID="SquareColumn">
    <rdfs:subClassOf rdf:resource="#Column"/>
  </owl:Class>
```

Instances

Similarly, the instances could be added into the ontology following the same syntax. For example, two types of square column are implemented in a building project, *“SquareColumn_01”* and *“SquareColumn_02”* which both are instances of the class *“SquareColumn”*. In OWL DL, these two instance are represented as:

```
<SquareColumn rdf:ID="SquareColumn_01">
<SquareColumn rdf:ID="SquareColumn_02">
```

Relationships

The relationships between these objects such *"column has concrete"* are defined as Object Property in OWL DL:

```
<owl:ObjectProperty rdf:ID="hasConcrete">
```

The Object Property provide the capability of defining relationships and restrictions on instance level in ontology. Taking the concrete used in building structure as an example, each column is composed of a specific type of concrete. *"SquareColumn_01"* and *"RC28_35_1"* are defined as instances of classes *"SquareColumn"* and *"Concrete"* respectively and connected with each other using a set of inverse Object Property *"hasConcrete"* and *"isConcreteOf"*. The following OWL DL illustrates the relationship between these two instances:

```
<owl:ObjectProperty rdf:ID="hasConcrete">
  <owl:inverseOf>
    <owl:ObjectProperty rdf:ID="isConcreteOf"/>
</owl:inverseOf>
<rdfs:range rdf:resource="#Concrete"/>
<rdfs:domain rdf:resource="#Column"/>
</owl:ObjectProperty>
...
<owl:ObjectProperty rdf:about="#isConcreteOf">
  <rdfs:domain rdf:resource="#Concrete"/>
  <owl:inverseOf rdf:resource="#hasConcrete"/>
  <rdfs:range rdf:resource="#Column"/>
 </owl:ObjectProperty>
...
<SquareColumn rdf:ID="SquareColumn_01">
<hasConcrete rdf:resource="#RC28_35_1"/>
```

Rules

In addition to the facts, the logic rules and constraints of problem domain are captured as a set of SWRL rules in OntoSCS knowledge base. Since the ontology and SWRL are integrated using homogeneous approach, the rules set in knowledge base is also represented as OWL DL language. The following example demonstrate an OWL DL representation of a SWRL rule.

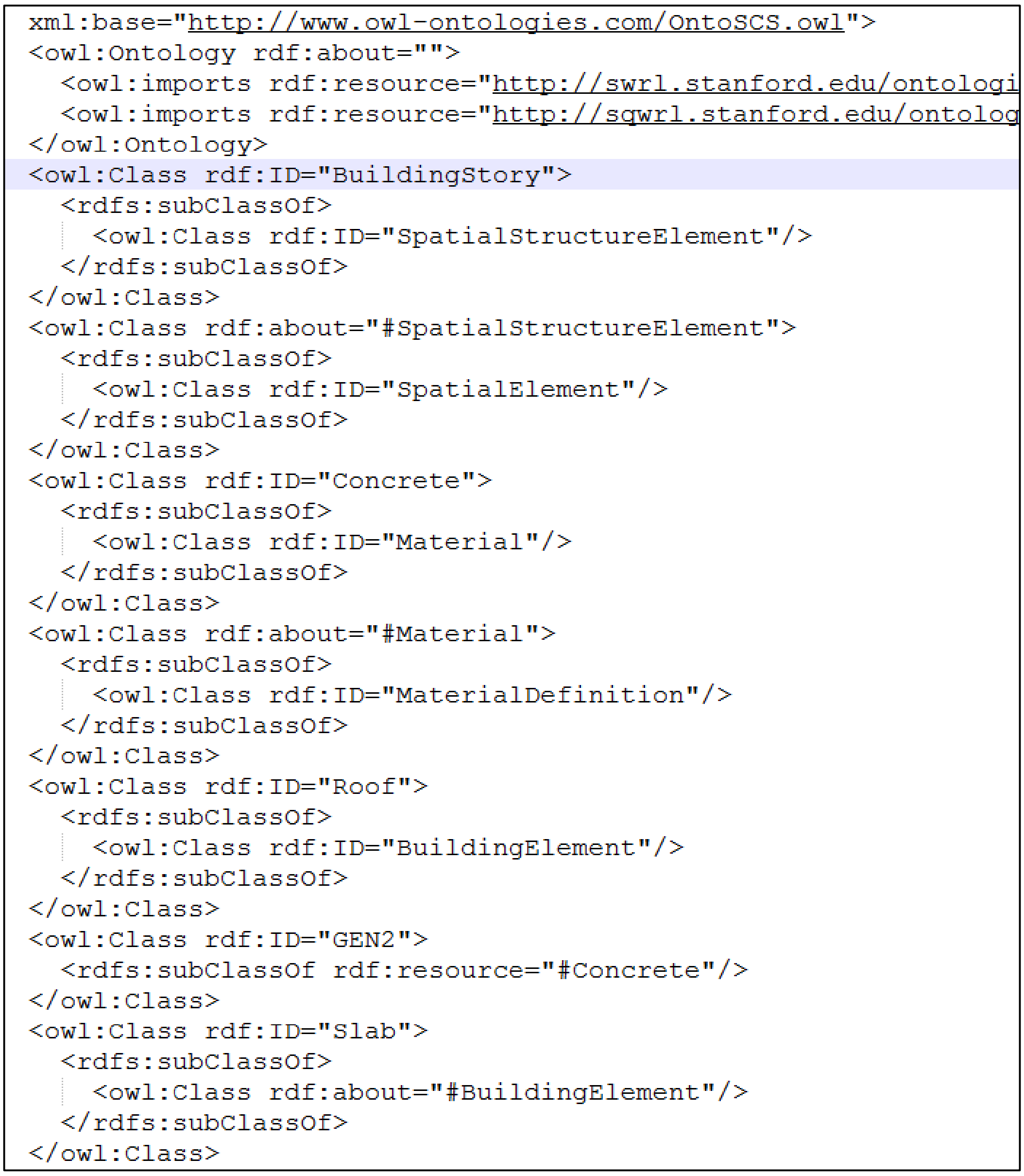
SWRL Rule - Defining suitable exposure class XC1
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) *∧ swrlb:greaterThanOrEqual(?Confck, 25)* *∧ Cover(?C, ?CC) ∧ swrlb:greaterThanOrEqual(?CC, 15)* *→ isExposedTo(?C, XC1)*

OWL DL format:

```
<swrl:Imp rdf:ID="Rule_Defining_Suitable_Exposure_Class_XC1">
…
<swrl:argument2 rdf:resource="#XC1"/>
<swrl:argument1 rdf:resource="#C"/>
<swrl:propertyPredicate rdf:resource="#isExposedTo"/>
…
<swrl:classPredicate rdf:resource="#SquareColumn"/>
<swrl:argument1 rdf:resource="#C"/>
…
<swrl:argument2 rdf:resource="#Con"/>
<swrl:argument1 rdf:resource="#C"/>
<swrl:propertyPredicate rdf:resource="#hasConcrete"/>
…
<swrl:argument1 rdf:resource="#Con"/>
<swrl:classPredicate rdf:resource="#Concrete"/>
…
<swrl:DatavaluedPropertyAtom>
<swrl:argument1 rdf:resource="#Con"/>
<swrl:argument2 rdf:resource="#Confck"/>
```

```
<swrl:propertyPredicate rdf:resource="#fck"/>
...
 <rdf:first rdf:resource="#Confck"/>
 <rdf:first rdf:datatype="http://www.w3.org/2001/XMLSchema#int>25</rdf:first>
...
 </swrl:arguments>
 <swrl:builtin rdf:resource="http://www.w3.org/2003/11/swrlb#greaterThanOrEqual"/>
 </swrl:BuiltinAtom>
...
<swrl:DatavaluedPropertyAtom>
<swrl:propertyPredicate rdf:resource="#Cover"/>
<swrl:argument2>
<swrl:Variable rdf:ID="CC"/>
...
<rdf:first rdf:resource="#CC"/>
<rdf:first rdf:datatype="http://www.w3.org/2001/XMLSchema#int">15</rdf:first>
...
</swrl:arguments>
<swrl:builtin rdf:resource="http://www.w3.org/2003/11/swrlb#greaterThanOrEqual"/>
</swrl:BuiltinAtom>
...
```

As the most important part in OntoSCS system, the knowledge base stores ontology model and SWRL rule set. There are two storing forms for the knowledge base. The first one is file format, such as XML, RDF and OWL. It is preferable for ontology applications that are developed by single ontology engineer. However, the persistency, scalability and sharability are relatively weaker compared with the second form. The second one is storing in database server. It provides a shared environment for multiple ontology developers. The selection of these two forms depends on that if the ontology needs to be built by single or more developer. Therefore, a single OWL file is chosen as the knowledge base form. Figure 4.6 shows partial OntoSCS ontology in OWL file presented in RDF/XML syntax.



```
xml:base="http://www.owl-ontologies.com/OntoSCS.owl">
<owl:Ontology rdf:about="">
  <owl:imports rdf:resource="http://swrl.stanford.edu/ontologi
  <owl:imports rdf:resource="http://sqwrl.stanford.edu/ontolog
</owl:Ontology>
<owl:Class rdf:ID="BuildingStory">
  <rdfs:subClassOf>
    <owl:Class rdf:ID="SpatialStructureElement"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:about="#SpatialStructureElement">
  <rdfs:subClassOf>
    <owl:Class rdf:ID="SpatialElement"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Concrete">
  <rdfs:subClassOf>
    <owl:Class rdf:ID="Material"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:about="#Material">
  <rdfs:subClassOf>
    <owl:Class rdf:ID="MaterialDefinition"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Roof">
  <rdfs:subClassOf>
    <owl:Class rdf:ID="BuildingElement"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="GEN2">
  <rdfs:subClassOf rdf:resource="#Concrete"/>
</owl:Class>
<owl:Class rdf:ID="Slab">
  <rdfs:subClassOf>
    <owl:Class rdf:about="#BuildingElement"/>
  </rdfs:subClassOf>
</owl:Class>
```

Figure 4.6 Excerpt of OntoSCS OWL file in RDF/XML syntax.

Inference rule engine

Inference rule engine reads the existing facts defined by the knowledge engineer in knowledge base, which are ontology and rules in this case, to deduct new facts by applying rules and to assert new facts into knowledge base. Since SWRL is a descriptive language that is independent of any rule language internal to rule engines, OWL and SWRL based regulation knowledge is required to be transformed into the rules expressed in the rule language of some rule engine (Zhong et al., 2012).

To implement OntoSCS system, a forward-chaining rule engine is employed in this research to perform the inference processes. A rule engine for the java platform, JESS (Java Expert System Shell), is adopted. The JESS uses the forward-chaining reasoning method and implements the efficient Rete algorithm to process a number of rules. The communications between ontology and rules engine are achieved by the bridge plug-in of ontology management system, for example SWRLJessBridge in this study.

The mechanism of reasoning conducted by JESS inference engine is explained in Figure 4.7. It contains three essential processes to perform the reasoning: (1) transformation from the structured knowledge in OWL into JESS facts, (2) transformation from logic/constraint knowledge in SWRL into JESS rules, (3) and actual inference by JESS matching the facts in fact base in accordance with the rules in rule base. In the former two processes, translators are required to map OWL-based and SWRL-based knowledge to JESS facts and rules respectively. Two translators namely OWL2JESS and SWRL2JESS are employed for this purpose. Both OWL2JESS and SWRL2JESS are developed using the Extensible Style-sheet Language Transformations (XSLT) to perform the transformation from XML documents to JESS files.

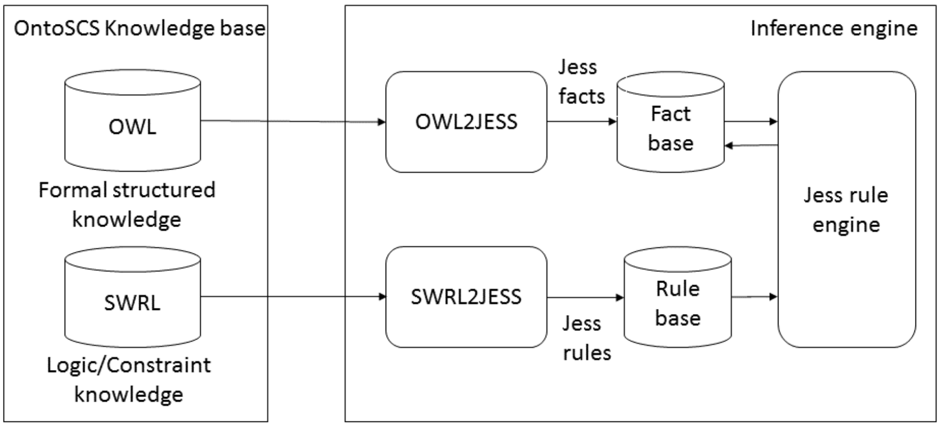


Figure 4.7 Reasoning process using JESS rule engine.

The classes in OWL DL ontology are mapped onto the JESS templates that define the types of JESS facts. For example, the three level class hierarchy *“BuildingElement”*, *“Column”* and *“SquareColumn”* are transformed into following JESS templates, where the *“deftemplate”* is used to define the type of slots in a fact; while the *“extends”* indicates the hierarchy relationship between two templates:

JESS templates
(deftemplate owl:Thing (slot name))
(deftemplate Column extends BuildingElement)
(deftemplate SquareColumn extends Column)

The instances of the OWL ontology are mapped onto JESS facts. For example, an instance of *“SquareColumn”* class, *“SquareColumn_01”* is transformed into JESS fact through OWL2JESS. The *“assert”* in JESS fact declare a fact that *“SquareColumn_01”* is an instance of the *“SquareColumn”*.

JESS Fact
(assert (owl:Thing (name SquareColumn_01)))
(assert (BuildingElement (name SquareColumn_01)))
(assert (Column (name SquareColumn_01)))
(assert (SquareColumn (name SquareColumn_01)))

Similarly, the SWRL rules in knowledge base is transformed into JESS rules using SWRL2JESS translator. For example, the rule defining the suitable exposure class for concrete structure is transformed into following JESS rule:

SWRL Rule - Defining suitable exposure class XC1

```
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck)
 ∧ swrlb:greaterThanOrEqual(?Confck, 25)

 ∧  Cover(?C, ?CC) ∧ swrlb:greaterThanOrEqual(?CC, 15)
 → isExposedTo(?C, XC1)
```

JESS rule

```
(defrule Defining suitable exposure class XC1
(SquareColumn (name ?C)) (hasConcrete ?C ?Con) (Cover ?C ?CC)
(Concrete (name ?Con)) (fck ?Con ?Confck)
(Concrete (?fck>=25)
(SquareColumn (?CC>=15)
=>
(assert (isExposedTo ?C ?XC1))
```

Ontology management system

In development of ontology based knowledge system, the integration of knowledge base and inference rule engine is often realised through ontology management systems. In the last decade, a number of ontology management systems has been developed, which is built of similar set of basic components providing core functions (Davies et al., 2009). Figure 4.8 demonstrates a typical ontology management system architecture. The ontology model is the core part of the architecture, which can be accessed and modified by the ontology editor. The reasoning engine communicates with ontology model through ontology management system API. The query interface supports standard query language so that end user could interact with system to obtain meaningful answers.

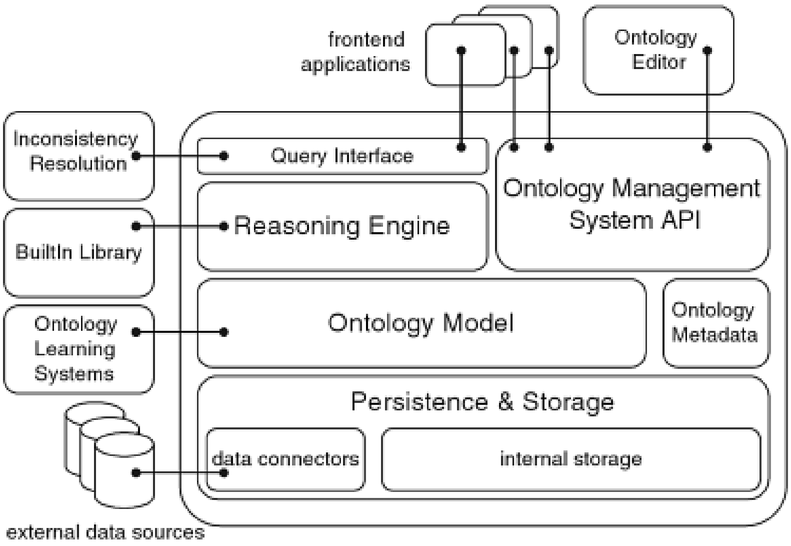


Figure 4.8 ontology management system architecture (Davies 2009).

In this work, Protégé-OWL 3.5 is employed as this role because of the following reasons. Firstly, Protégé-OWL 3.5 is an open-source tool developed by Stanford University that enables end users to create and update ontologies, which is available for free. Secondly, it is the most popular and advanced ontology editor in nowadays. Thus, there are mature online community and developers all over the world supporting it. Abundant learning resource and concise implementation guides of Protégé are available for ontology developers who are unfamiliar with software engineering or have no experience with developing ontology. Thirdly, one advantage of Protégé is that it is compatible with most OWL syntax validators. Furthermore, many plug-ins have been developed to extend the capability of Protégé in different use scenarios; for example, the SWRLTab and JambalayaTab for editing SWRL rules and visualisation of ontology. Additionally, Protégé could be further integrated with other software development environment or database management system. To check the consistency of ontology, reasoner Pellet 1.5.2 is deployed in this system as the reasoning engine. End users such as structural engineers could 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 summary, the architecture of OntoSCS system is an integration of three core components: knowledge base, ontology management system and inference rule engine. Figure 4.9 illustrates the architecture and workflow that is composed of a number of key tasks:

1. Knowledge engineer converted the human knowledge into OWL DL ontology and SWRL rules;
2. Through ontology and rule editors (Protégé main interface and SWRLTab), ontology and SWRL rules are edited and stored in knowledge base (an OWL file in this case);
3. Inference rule engine (JESS engine) reads the existing facts in ontology, and applying SWRL rules and generating new facts to knowledge base;
4. End users input design requirements in the form of SQWRL query through query interface (SQWRLQueryTab), and obtain feasible results.

The key techniques and system components are presented in Table 4.1.

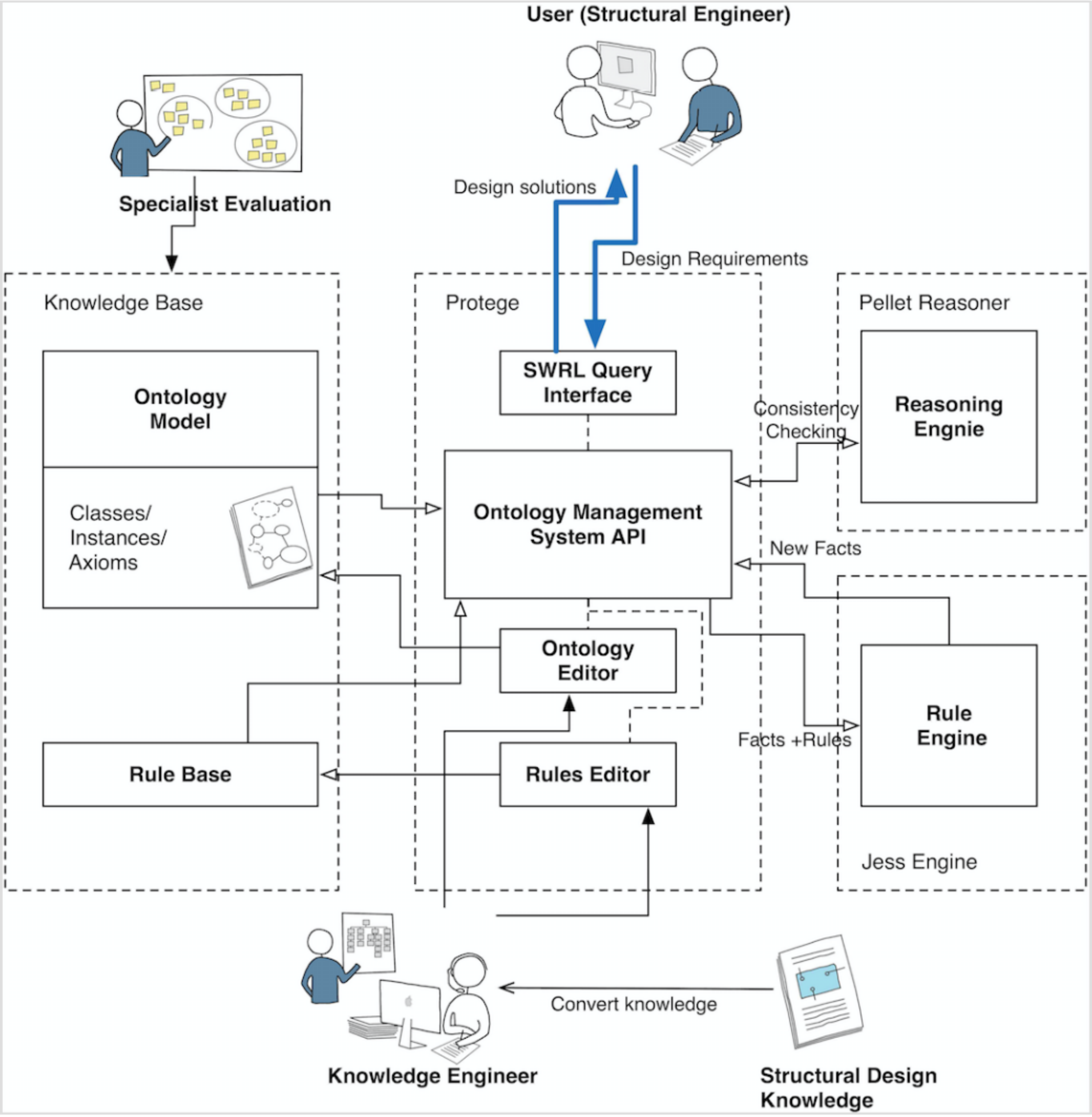


Figure 4.9 System architecture of OntoSCS prototype system.

Table 4.1 Key techniques and components of OntoSCS system.

Techniques/Components	***Choice***	***Justification***
Ontology languages	OWL DL	High expressiveness with decidability, supported by reasoning engine.
Rule language	SWRL	Tight integration with OWL DL, rich built-ins, easily handling condition rules
Query language	SQWRL	Built on SWRL, native understanding of OWL
Ontology management system	Protégé 3.5	Easy-to-use interface, abundant learning resources and plug-ins
Rule engine	JESS engine 71P2	Powerful rule engine for knowledge-based system, supports SWRL rule format
Rule and query editor	SWRLTab	The only Protégé-OWL 3.5 plug-in for editing and running SWRL rules
Rule engine bridge	SWRL Jess Bridge	Plug-in for connecting ontology and JESS engine
Query interface	SQWRLQueryTab	Integrated with SWRLTab, provides a graphical interface to work with SQWRL queries
Rule reasoning interface	SWRLJessTab	Supports the execution of SWRL rules, provides a graphical interface to interact with JESS rule engine.
Ontology visualisation	JambalayaTab	Flexible layouts of ontology visualisation
Rule visualisation	AxiomeTab	Clear illustration of logic relationship of SWRL rules
Validation reasoning engine	Pellet 1.5.2	Embedded with Protégé-OWL 3.5 for consistency checking

4.3 Summary

This chapter has explained the design of the prototype system to be implemented in this research. The identification of system requirements, design of system architecture, and configuration of system key components are presented respectively.

Defining system requirements is a primary task before the system development. It outlines the functions, performance and resilience of this system. Determined by the system requirements, the system architecture has been designed. Taking the generic Semantic Web based information system architecture N-tier model as a design reference, the prototype system consists of three essential segments: knowledge base, ontology management system and inference rule engine. The OntoSCS ontology and associated SWRL rule set compose the knowledge base that is stored in the form of OWL file. Protégé-OWL 3.5 is used as the ontology management system providing ontology and rule editing, SWRLTab plug-ins, reasoners and other functions required for prototype system development. JESS engine is the inference rule engine applied in this system, which is bridged by Protégé-OWL to provide reasoning function. The ensuing Chapter 5 describes the implementation of the prototype system OntoSCS in a step-by-step manner following the Ontology Development 101 methodology.

Chapter 5 OntoSCS System Development

Having established the framework of prototype system, it is necessary to implement it in software environment. On completion of system architecture, this chapter introduces the implementation of OntoSCS system in Protégé environment. The sustainable structural design knowledge base has been developed in two contexts. Firstly, ontology editor is used to construct the OntoSCS ontology, then a rule set composing of SWRL rules and SQWRL queries is developed to enhance the knowledge base with reasoning and retrieval functions. One of the main challenges was that the knowledge elicited from literature resources needs to be transformed accurately into the corresponding components of proposed system architecture, following the ontology methodology introduced in Chapter 3. The key steps of transform procedure will be introduced in Section 5.2. Furthermore, in Section 5.4, the development of SWRL rules and SQWRL queries is presented with examples.

5.1 Domain knowledge acquisition

In order to develop a knowledge-based decision support system, it is crucial to understand the complex structure of domain knowledge before capturing it in the knowledge base. Accordingly, this section aims to provide an understanding of structural design domain and associated sustainability domain, including the key concepts, features and relationships. Due to the limit time and resource of this research, it is difficult to explore all types of building structure. Therefore, a generic framework of knowledge model that covers essential structural concepts is built. Based on the framework, concrete structural design is illustrated in detail, with the intention to provide an applicable example for full range of structural design domain.

The domain knowledge acquisition is a preparation process for formal ontology development. CommonKADS knowledge engineering methodology previously introduced in Chapter 3 is adopted in this preparation process, which consists of three steps:

Step 1: Knowledge Identification

This step is used to conclude the problems in the domain, the purpose of the knowledge model, and the scope of the model. There are two key activities conducted in this step: domain familiarisation and identification of potential model component. Firstly. references of the targeting domain, including structural design codes, government standards and documents, sustainable design guidance, websites and peer-reviewed papers are reviewed and analysed. The main outcome of this activity is to understand the sustainable structural design domain, including the identification of its characteristics, current methods, barriers and potential solutions. Secondly, existing knowledge models or semantic sources are surveyed thoroughly. Some reusable ontology examples in construction domain are e-COGNOS ontology and ifcOWL ontology published by W3C community based on IFC4_ADD1. At the end of this step, the relevant domain concepts are elicited and a glossary of these terms is constructed. Elicited domain concepts consist of three categories:

1. Building structure concepts such as column, beam, slab, concrete and reinforcement are summarised from design codes or guides;

2. Concepts and parameters related to structural design principles; for example, strength class and other characteristics of concrete are extracted from BS 8500 Standard (British Standards Institution, 2015);

3. Sustainability data; for instance, the values of embodied energy and CO_2e applied in this study are chosen from ICE database (Jones, 2011) .

Step 2: Knowledge Specification

The main task in this step is to construct a specification for the knowledge model. It involves choosing a template and then building up a semi-formal modelling which can be executed using any modelling language such as the UML in this case (Kogut et al., 2002). The re-usable resources identified in the first step are also taken into consideration when construct the model. Figure 5.1 illustrates the specified knowledge model in an UML class diagram. The top-level concepts elicited from ifcOWL ontology constructs the generic framework of structural design knowledge model. Concepts related to the concrete structure such as cement, reinforcing bar and concrete are populated into the framework as sub-classes. The extracted concepts from structural design domain such as column, reinforcing bar and concrete are organised in a hierarchical structure, while the factors affecting sustainability include 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 associations of UML including their multiplicities have been used to relate the top level concepts. For example, the multiplicity of *1. . .** on the association *"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 can be manually edited in Protégé-OWL environment following the Ontology Development 101 methodology.

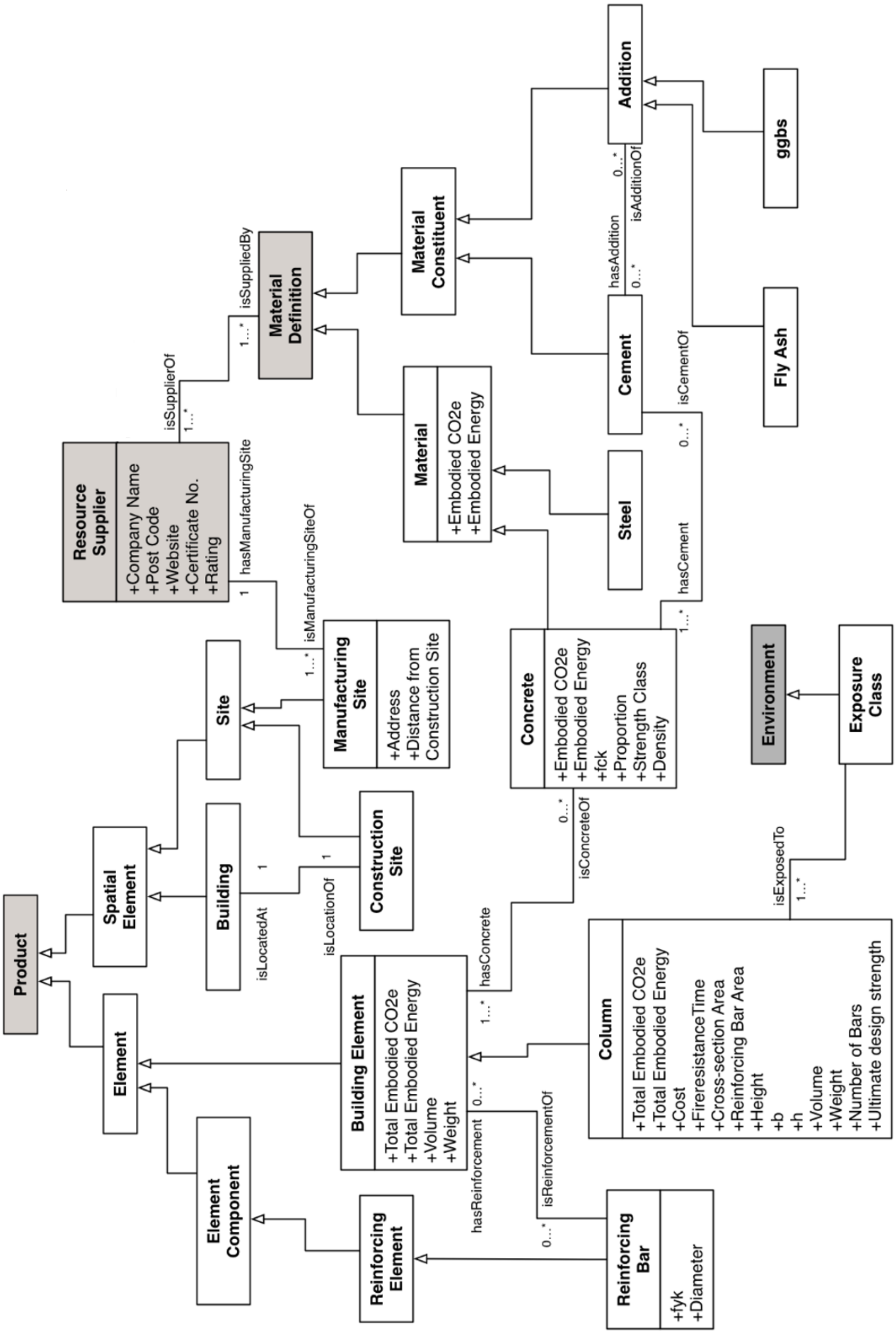


Figure 5.1 UML class diagram of key concepts of OntoSCS ontology.

The challenge remains when transforming the OntoSCS UML model into Protégé-OWL ontology model. To overcome this challenge, there are two approaches available: the UML-OWL conversion tool and manual conversion approach. The initial attempt of using the UML-OWL conversion tool is not suitable due to the data loss issues. Thus, the manual conversion approach has been adopted in this study. Different elements in UML model are transformed into OWL ontology model by following conversion rules listed in Table 5.1.

Table 5.1 Conversion rules from UML to OWL.

UML	***OWL***
Class	Class
Generalisation of classes	Superclass
Association	Object Property
Attribute	Data-type Property
Multiplicity	Functional Object Property

Step 3: Knowledge Refinement

This is the final step of knowledge modelling. Two main tasks are undertaken, knowledge model validation and refinement, where refinement is the completion of knowledge modelling. The entire process normally will be repeated several times and each step is also an iterative process. In addition, it is recommended to develop a prototype before the development of full version of knowledge model. In this case, knowledge refinement is carried out as ontology evaluation process presented in Section 5.3. The completion of the preparation tasks has accomplished a considerable portion of the formal ontology development; for example, the determination of domain scope, reuse of existing semantic resource, enumeration of terms, and arrangement of class hierarchy. However, since ontology development is an iterative process, some of the tasks that have been accomplished in preparation will be repeated in the formal development process presented in the ensuing section to refine the ontology.

5.2 Development of OntoSCS ontology

Seven key steps have been concluded to develop OntoSCS ontology following the Ontology Development 101 methodology, they are listed below:

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. 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 build this ontology?

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

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

A: Structural design and building sustainability (including structural feasibility, durability, fire safety, embodied energy and CO_2e in building materials, cost, material supplier selection).

- 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.

- Q: What are sources for the knowledge elicitation?

  A: Structural design codes, guides, national standards, database for carbon footprint, websites, as listed in Table 5.2.

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: Structural 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, exposure class, fire resistance, cost and distance of transport.

(d) Q: How to measure the sustainability of materials?

A: Embodied energy and CO_2e for environmental aspect, and cost for economic aspect.

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.

Table 5.2 Knowledge sources of OntoSCS ontology.

Knowledge source	***Type***	***Publisher***
BS EN 1992 Eurocode 2: Design of concrete structures	Structural design code	European Committee for Standardisation
Reinforced Concrete Design to Eurocode 2	Design guide	Palgrave Macmillan
Specifying Sustainable Concrete	Design guide	The Concrete Centre
BS 8110-1:1997 Structural use of concrete	British standard	British Standards Institution
BS 8500-1:2015 Concrete. Method of specifying and guidance for the specifier	British standard	British Standards Institution
BS EN 15643-1:2010 Sustainability of construction works	British standard	British Standards Institution
BES 6001, BRE Environmental & Sustainability Standard Framework Standard for the Responsible Sourcing of Construction Products	British standard	British Standards Institution
Embodied CO_2 of Concrete and Reinforced Concrete	Technical report	Mineral Product Association
Embodied energy and carbon - The ICE database	Database	http://www.circularecology.com
Spon’s Civil Engineering and Highway Works Price Book 2015	Book	CRC Press
Responsible Sourcing of Construction Products	Website	http://www.greenbooklive.com

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, 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 (Roussey et al., 2011). It offers an example of structuring concepts associated with building elements; however, with limitations of rule restrictions. The W3C recently has published the ifcOWL as a common reference ontology. It is converted from EXPRESS schema of IFC for interoperability and reasoning purpose. Thus, the OntoSCS ontology extends ifcOWL ontology with addition of more specific relationships and restrictions for sustainable structural design. Figure 5.2 demonstrates the mapping relationship between the top-level classes in ifcOWL ontology and classes in OntoSCS ontology. Additionally, existing classification in building construction domain such as Uniclass (Unified Classification for the Construction Industry) is partially considered to share a common vocabulary library with other ontologies in this domain.

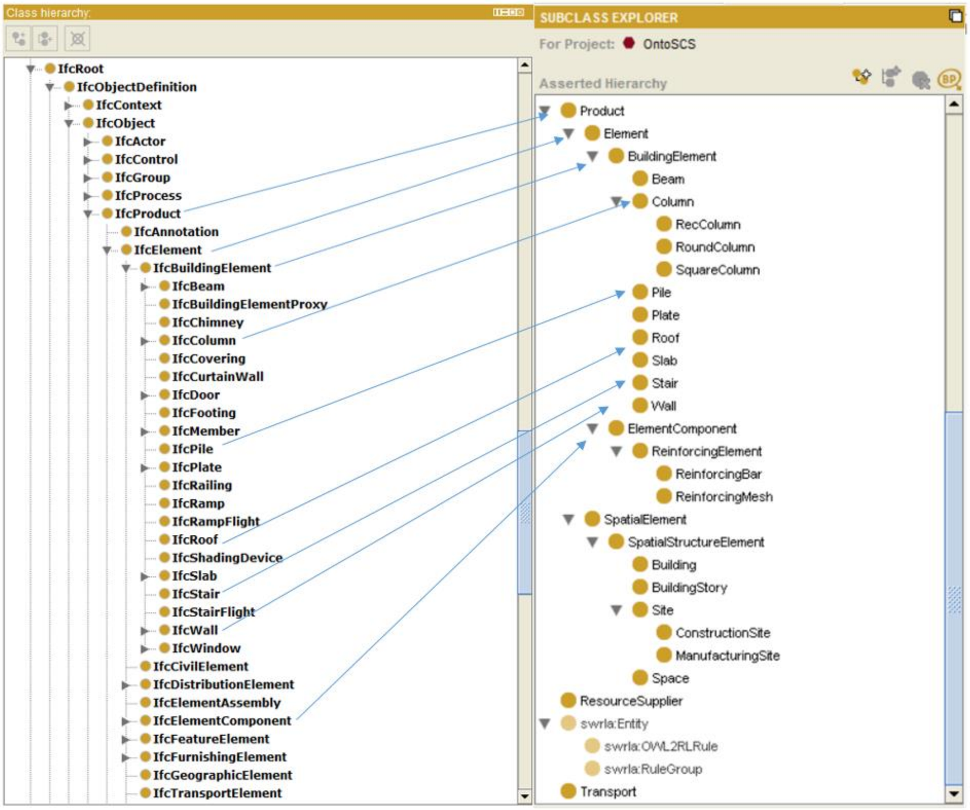


Figure 5.2 Top-level concepts mapping from ifcOWL ontology.

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 5.3 are imported from ICE database (Jones, 2011) to the ontology. Additionally, the information of material suppliers is collected from GreenBookLive website (BRE Global, 2014).

Table 5.3 Embodied Energy and Carbon from ICE database.

Material	***Embodied Energy - MJ/kg***			***Embodied Carbon - kgCO$_2$e/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 4. Define the classes and the class hierarchy

A variety of methods have been used to develop class hierarchy and each of them has its advantages and drawbacks (Uschold and Gruninger, 1996). Since the OntoSCS ontology is created from existing classification and ifcOWL, the partial hierarchy of ifcOWL is inherited. A top–down development process is adopted, where the most general domain concepts are defined first then for those subclass concepts. In the developed OntoSCS, the general concepts include *Product*, *MaterialDefinition*, *Environment* and *ResourceSupplier*, which the former two come from ifcOWL and the last two is created specifically for this ontology. The general concepts have been further broken down into more specific sub-concepts such as *Building*, *Site*, *Material* and *MaterialConstituent* by following the class hierarchy of ifcOWL. All subclasses inherit certain properties of super classes. For example, all the properties of *BuildingElement* will be inherited by 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 *BuildingElement* instead of *Column*, since it is the most general class whose instance and subclasses will have volume. The developed classes are presented in Table 5.4, and overall taxonomic hierarchy of defined OntoSCS ontology is demonstrated in Figure 5.3.

Table 5.4 Classes of OntoSCS ontology.

Root Classes	***Subclasses***			
Environment	ExposureClass			
MaterialDefinition	Material	Concrete Steel Wood		
	MaterialConstituent	Addition	FlyAsh GGBS	
		Aggregate Cement		
Product	Element	BuildingElement	Beam	
			Column	RecColumn RoundColumn SquareColumn
			Pile Plate Roof Slab Stair Wall	
		ElementComponent	Reinforcement	ReinforingBar ReinforcingMesh
	SpatialElement	SpatialStructureElement	Building BuildingStory	
			Site	ConstructionSite ManufacturingSite
			Space	
ResourceSupplier				

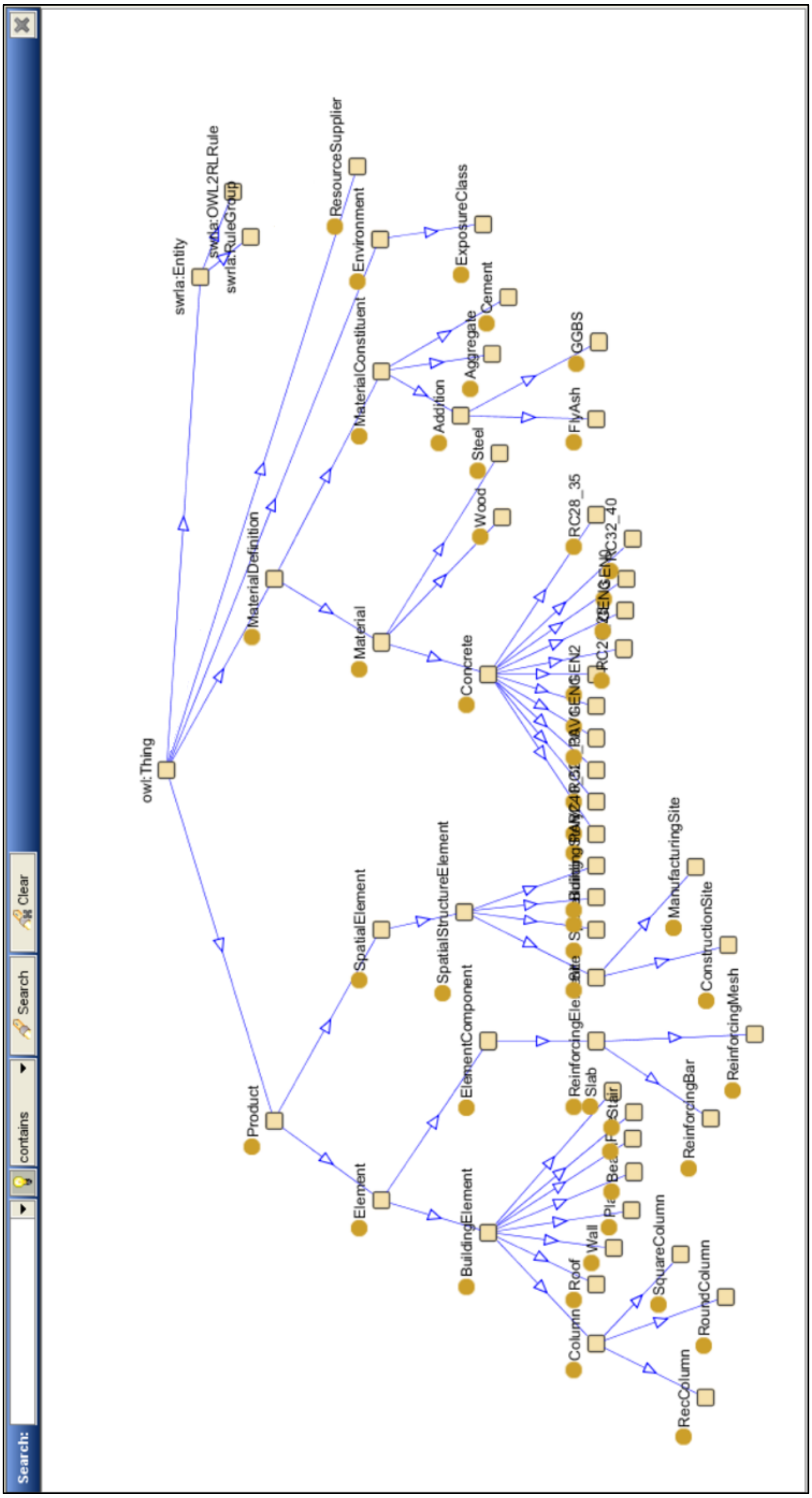


Figure 5.3 Class hierarchy of OntoSCS ontology.

Step 5. Define the properties of classes

Since the class hierarchy itself is not adequate 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.

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. Figure 5.4 demonstrates conversion from UML associations of knowledge model to object properties in OntoSCS ontology.

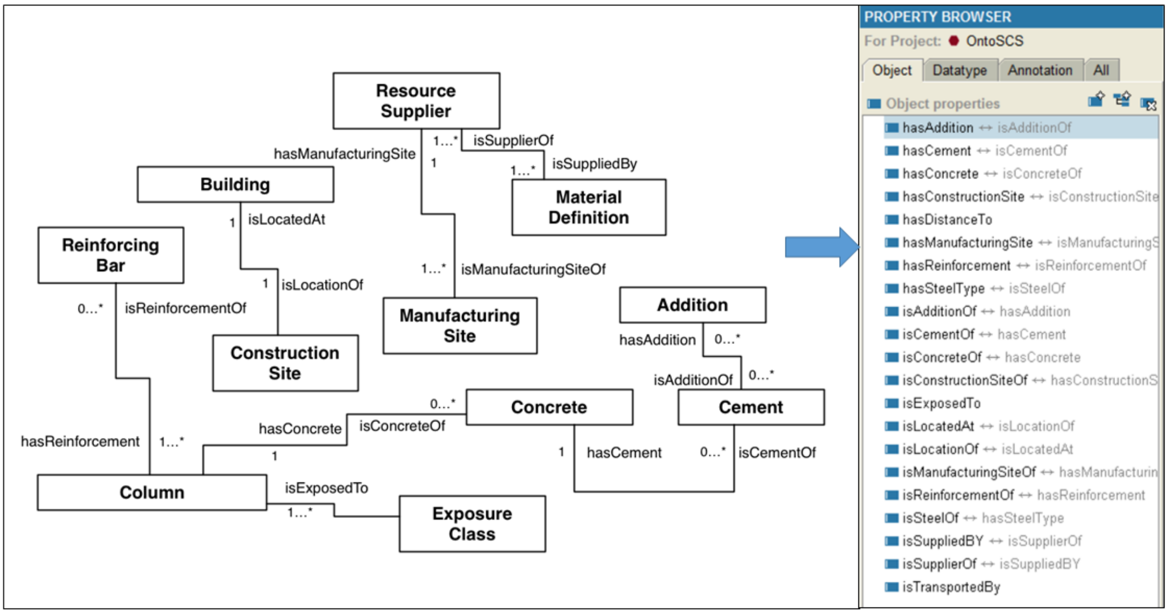
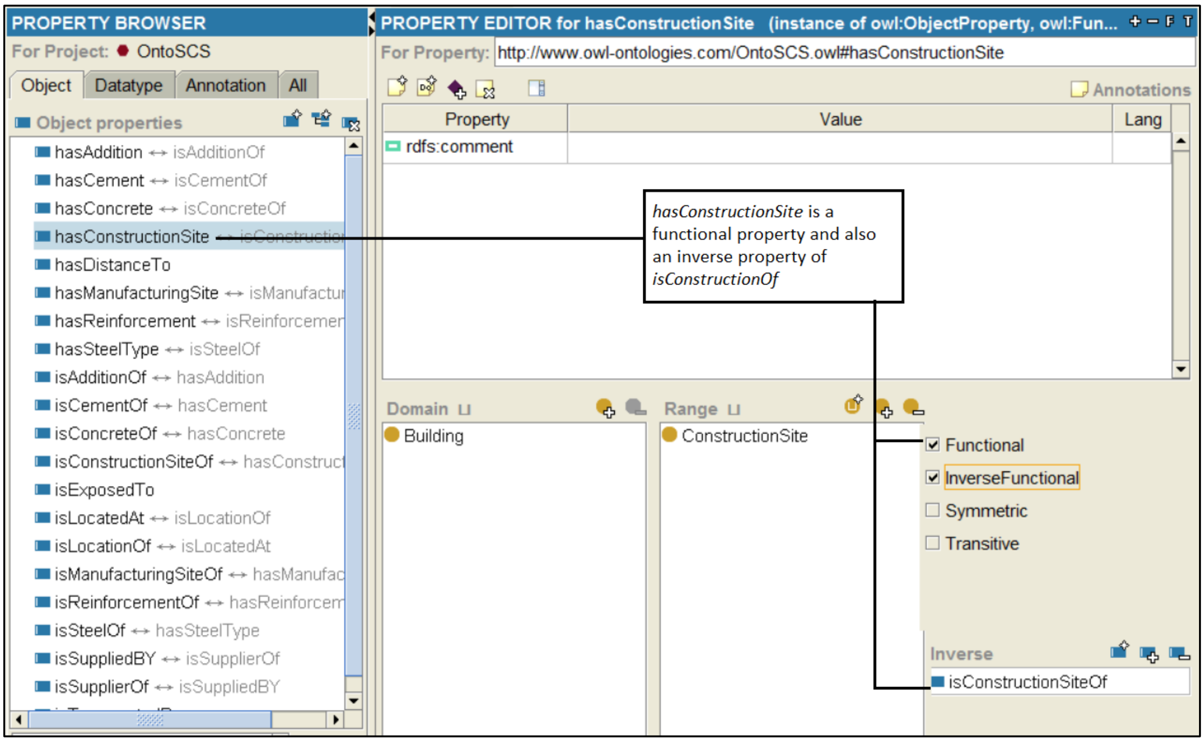


Figure 5.4 Conversion from UML associations to object properties in ontology.

Object properties can be defined as functional, inverse, symmetric, and transitive:

- Functional properties can only have one single value for instance. For instance, the object property *hasConstructionSite* with domain *Building* and range *ConstructionSite* is defined as functional since a building can only have one construction site.

- If an object property links individual A to B, then its inverse property links individual B to A. Figure 5.5 shows an example of inverse object property in OntoSCS ontology *"hasConstructionSite"*. It defines the relationship between an instance *"Building_1"* in *"Building"* class and *"ConstructionSite_1"* in *"Construction"* class as *"Building_1 hasConstructionSite ConstructionSite_1"*. Accordingly, the inverse property *isConstructionSiteOf* could be defined to represent the opposite relationship of these two instances as *"ConstructionSite_1 isConstructionSiteOf Building_1"*.



For Property: http://www.owl-ontologies.com/OntoSCS.owl#hasConstructionSite

hasConstructionSite is a functional property and also an inverse property of *isConstructionOf*

Domain: Building

Range: ConstructionSite

☑ Functional
☑ InverseFunctional
☐ Symmetric
☐ Transitive

Inverse: isConstructionSiteOf

Figure 5.5 Inverse and functional property.

- A symmetric property is used to define relationship applied for both directions of two instances. For instance, *hasDistanceTo* is a symmetric property that can be applied to two construction site instances.

- The transitive property means if a property relates individual A to individual B, and also individual B to individual C, then individual A is related to individual C via same property. The example is *"isAdditionOf"* property, where the *"Flyash isAdditionOf Cement"* and *"Cement isAdditionOf Concrete"*.

Data-type property defines quantitatively and qualitatively characteristics of instances of classes. Common value types include string, number, Boolean and enumerated that 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 *"TotalECO*$_2$*e"*, *"CompanyName"* and *"Volume"* are populated under corresponding classes. Figure 5.6 demonstrates the conversion from UML attributes to data-type properties in OntoSCS ontology.

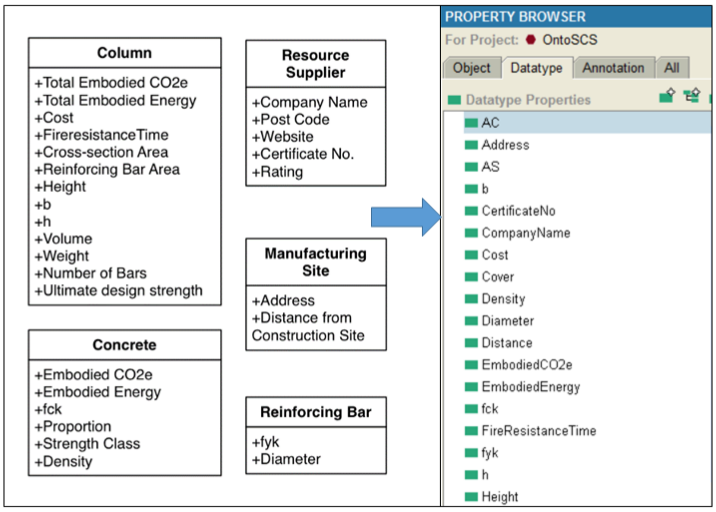
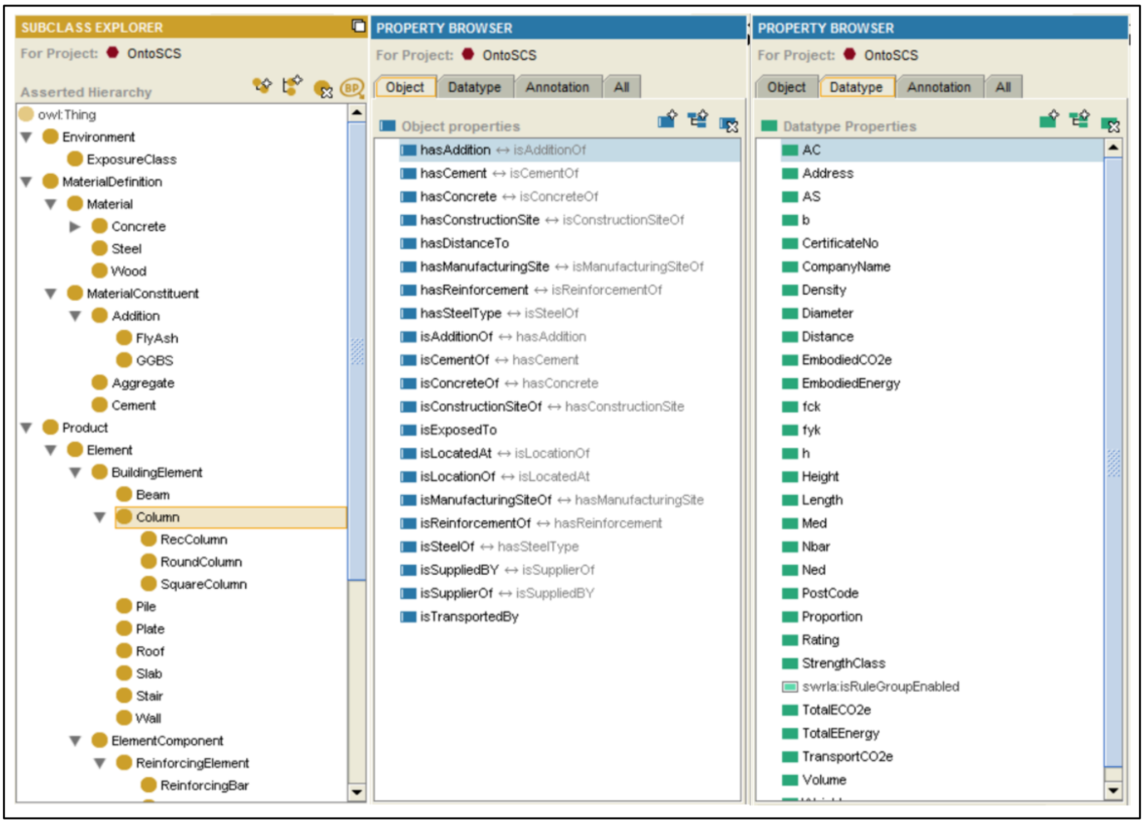


Figure 5.6 Conversion from UML attributes to data-type properties in ontology.

Annotation property is text comment on some elements of ontology, which is used to clarify data and explanation.

Having complete the step 5, the class hierarchy of OntoSCS ontology are enriched by connecting related classes with object properties, and defining attributes of classes with data-type properties. Figure 5.7 concludes all of the object and data-type properties developed in this ontology, while Figure 5.8 illustrates the developed OntoSCS ontology with class hierarchy and inner relationships.

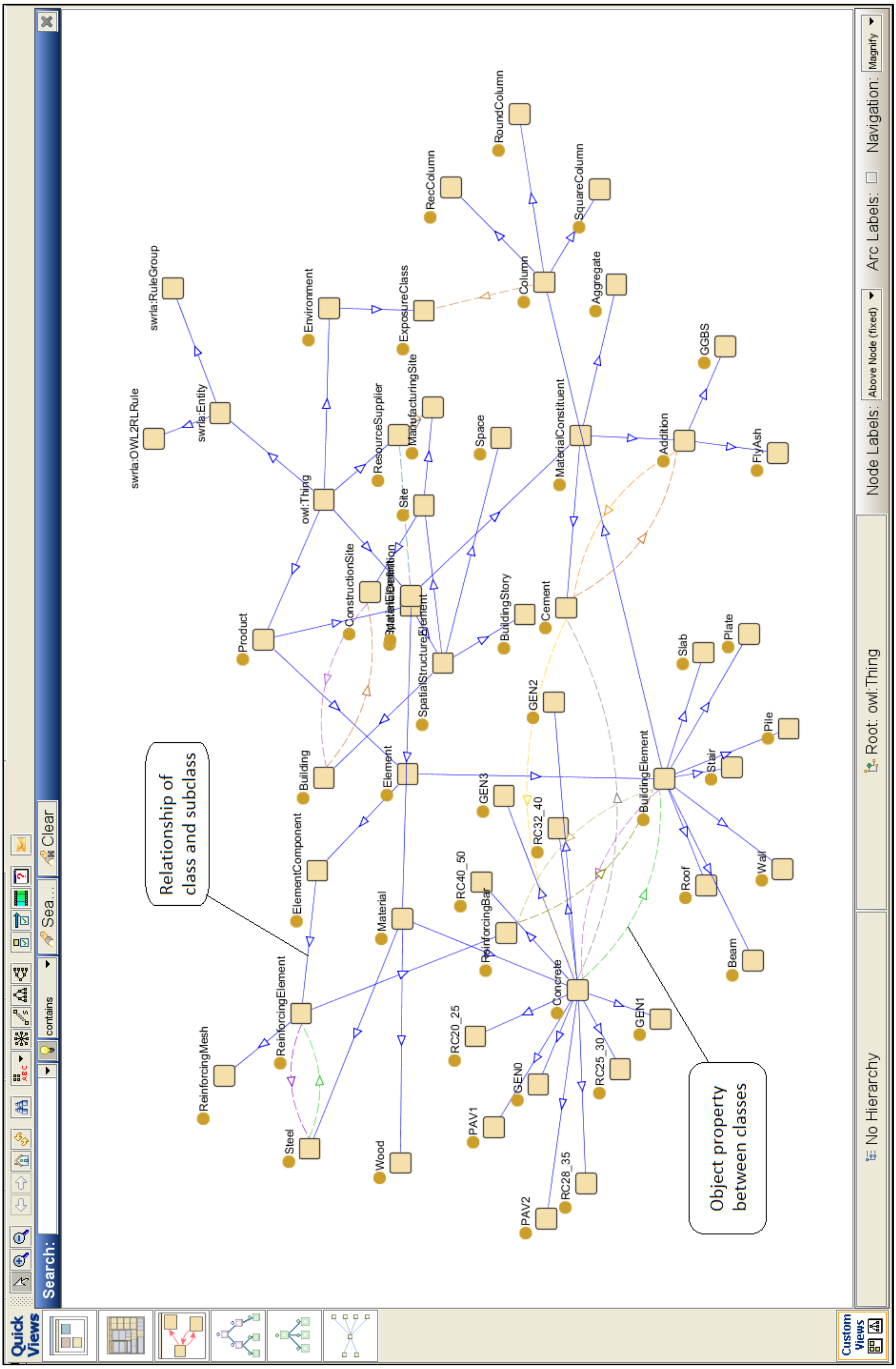


owl:Thing
- Environment
  - ExposureClass
- MaterialDefinition
  - Material
    - Concrete
    - Steel
    - Wood
  - MaterialConstituent
    - Addition
      - FlyAsh
      - GGBS
    - Aggregate
    - Cement
- Product
  - Element
    - BuildingElement
      - Beam
      - Column
        - RecColumn
        - RoundColumn
        - SquareColumn
      - Pile
      - Plate
      - Roof
      - Slab
      - Stair
      - Wall
    - ElementComponent
      - ReinforcingElement
        - ReinforcingBar

hasAddition ↔ isAdditionOf
hasCement ↔ isCementOf
hasConcrete ↔ isConcreteOf
hasConstructionSite ↔ isConstructionSiteOf
hasDistanceTo
hasManufacturingSite ↔ isManufacturingSiteOf
hasReinforcement ↔ isReinforcementOf
hasSteelType ↔ isSteelOf
isAdditionOf ↔ hasAddition
isCementOf ↔ hasCement
isConcreteOf ↔ hasConcrete
isConstructionSiteOf ↔ hasConstructionSite
isExposedTo
isLocatedAt ↔ isLocationOf
isLocationOf ↔ isLocatedAt
isManufacturingSiteOf ↔ hasManufacturingSite
isReinforcementOf ↔ hasReinforcement
isSteelOf ↔ hasSteelType
isSuppliedBY ↔ isSupplierOf
isSupplierOf ↔ isSuppliedBY
isTransportedBy

AC
Address
AS
b
CertificateNo
CompanyName
Density
Diameter
Distance
EmbodiedCO2e
EmbodiedEnergy
fck
fyk
h
Height
Length
Med
Nbar
Ned
PostCode
Proportion
Rating
StrengthClass
swrla:isRuleGroupEnabled
TotalECO2e
TotalEEnergy
TransportCO2e
Volume

Figure 5.7 Object properties and data-type properties in OntoSCS ontology.



Relationship of class and subclass

Object property between classes

No Hierarchy

Root: owl:Thing

Node Labels: Above Node (fixed)

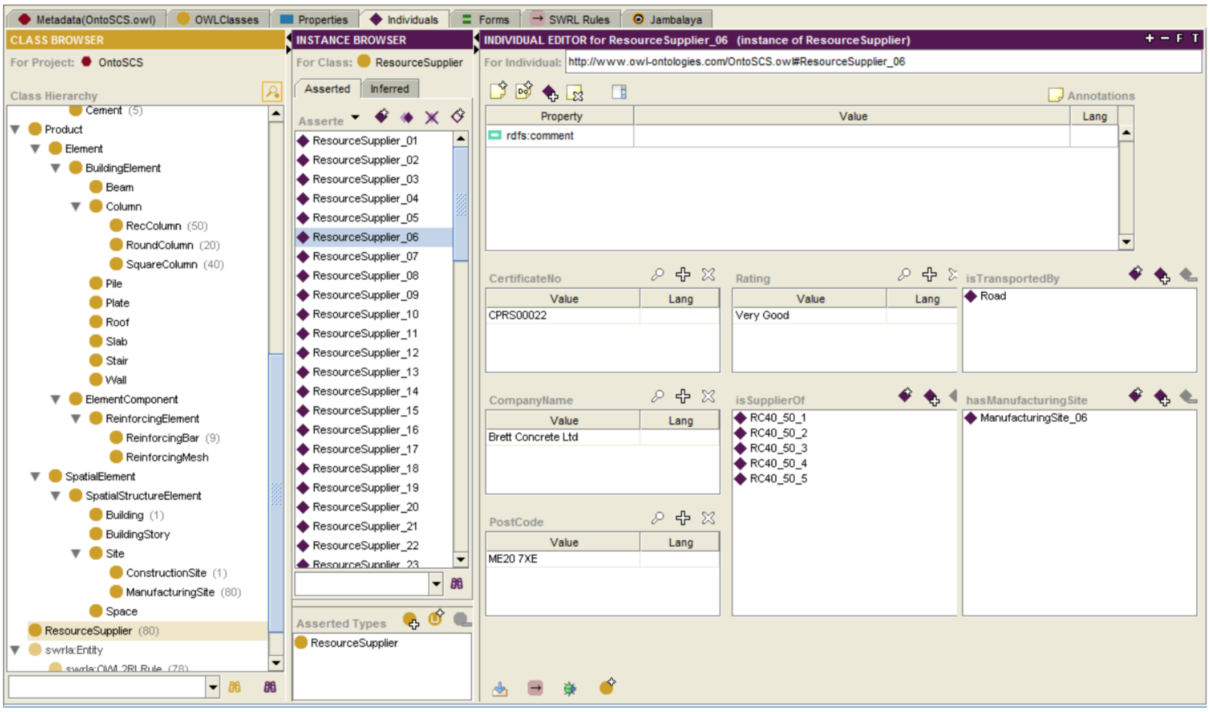
Arc Labels: ☐

Navigation: Magnify

Figure 5.8 Relationships between classes defined by object properties.

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. Various value types including strings, number and Boolean could be defined to the property. For example, the *Rating* of *ResourceSupplier* could be attributed qualitatively using strings to represent different levels of evaluation: *good*, *very good* and *excellent* as shown in Figure 5.9. On the other hand, the distance from *ResourceSupplier* to *ConstructionSite* can be measured quantitatively using numbers such as 224.49 km.



For Individual: http://www.owl-ontologies.com/OntoSCS.owl#ResourceSupplier_06

CertificateNo: CPRS00022

Rating: Very Good

isTransportedBy: Road

CompanyName: Brett Concrete Ltd

isSupplierOf: RC40_50_1, RC40_50_2, RC40_50_3, RC40_50_4, RC40_50_5

hasManufacturingSite: ManufacturingSite_06

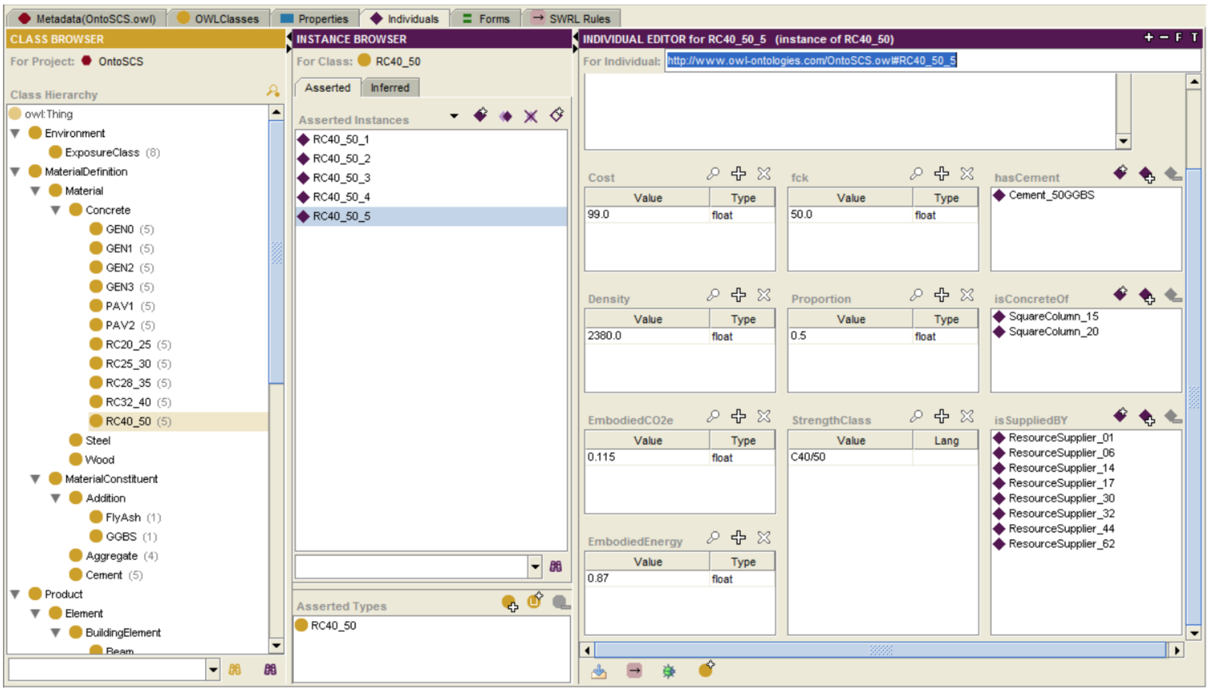
PostCode: ME20 7XE

Figure 5.9 Qualitative facet of property.

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 5.3 are populated into ontology as data-type properties of different concrete materials, as shown in Figure 5.10.



For Project: OntoSCS

For Class: RC40_50

For Individual: http://www.owl-ontologies.com/OntoSCS.owl#RC40_50_5

Property	Value	Type
Cost	99.0	float
fck	50.0	float
Density	2380.0	float
Proportion	0.5	float
EmbodiedCO2e	0.115	float
EmbodiedEnergy	0.87	float

StrengthClass: C40/50

hasCement: Cement_50GGBS

isConcreteOf: SquareColumn_15, SquareColumn_20

isSuppliedBY: ResourceSupplier_01, ResourceSupplier_06, ResourceSupplier_14, ResourceSupplier_17, ResourceSupplier_30, ResourceSupplier_32, ResourceSupplier_44, ResourceSupplier_62

Figure 5.10 Instances of Concrete class.

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. Using some built-in functions of SQWRL 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 are explained in the rule development section.

5.3 Semantic and syntactical validation of ontology

Ontologies are engineering artefacts that formally define the concepts in a knowledge domain. Like any engineering artefact, an ontology needs to be thoroughly evaluated (Vrandečić, 2009).

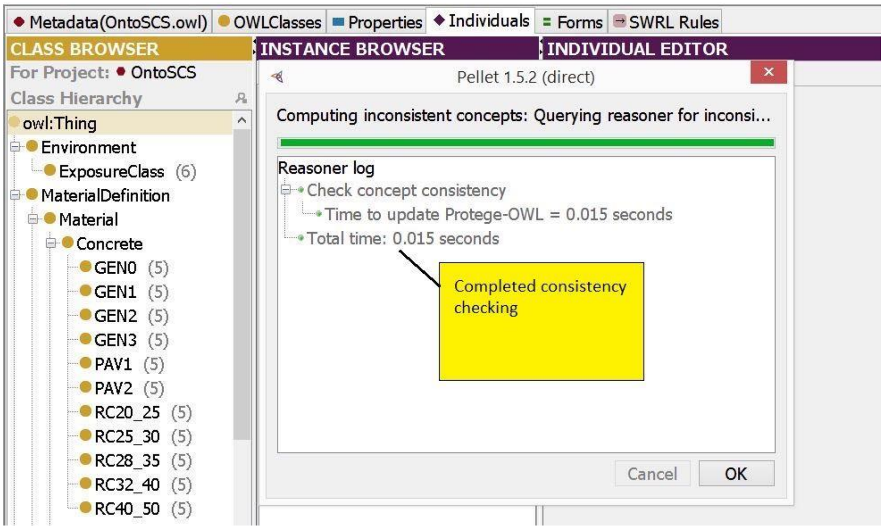
This activity consists of ensuring the semantic correctness, the syntactic correctness and to verify if the ontology meets the requirement conditions or does what it was intended to do. Gomez-Perez introduces the two terms ontology verification and validation for describing ontology evaluation: ontology verification deals with building the ontology correctly, that is, ensuring that its definitions implement correctly the requirements (Vrandečić, 2009). Ontology validation refers to whether the meaning of the definitions really models the real world for which the ontology was created. In this section, the first two validation activities are examined and a case study based validation will be presented in Chapter 6.

5.3.1 Semantic verification

In terms of semantic verification, two main methods can be applied depending on the ontology development approaches. If the ontology is developed from scratch, then the preferable method is manual validation by consulting domain experts and checking the concepts in proposed ontology model. The accuracy of this method is high yet with some drawbacks such as time consuming. 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. In this method, the proposed ontology is aligned or compared to another one that is often referred to as a reference or a golden standard, in order to find corresponding concepts that have same intended meaning. If the complete 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 expert reviews. Based on the fact that only some of the top level concepts of the OntoSCS ontology are elicited from ifcOWL instead of completely arising from existing ontologies, each concept is analysed and semantically validated manually by domain experts.

5.3.2 Syntactical verification

After semantically verifying the ontology, it is imperative to syntactically check its consistency. The developed ontology is checked against subsumption, equivalence, instantiation and consistencies. Currently, there are two major methods of performing consistency checking of an ontology, 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 Figure 5.11. After the syntactic verification, the ontology needs to be validated for the purpose for which it was developed. In Chapter 6, a case study with a group of applications is established to test if the OntoSCS ontology works as intended.



Pellet 1.5.2 (direct)

Computing inconsistent concepts: Querying reasoner for inconsi...

```
Reasoner log
Check concept consistency
  Time to update Protege-OWL = 0.015 seconds
Total time: 0.015 seconds
```

Completed consistency checking

Figure 5.11 Consistency checking using Pellet reasoner.

5.4 Development of SWRL rules

Besides to the knowledge such as buildings and structural members explicitly represented in OWL ontology, there are many other types of structural design knowledge expressed in the form of rules; for example, the requirement of ultimate load capacity and application rule of fire resistance. Based on these rules, implicit knowledge can be deducted from the explicit knowledge in ontology, and therefore meaningful conclusion can be drawn. As introduced in Chapter 3, one of the homogeneous approaches is adapted in this study for rule development, which provides a seamless semantic integration of rules and ontologies. More importantly, it offers 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 plug-in of Protégé-OWL. two types of semantic rules are used. SWRL rules is used for reasoning function. SQWRL (Semantic Query-Enhanced Web Rule Language), a SWRL-based query language, is used for querying OWL ontologies. As introduced in Chapter 2, 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 atom 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 whether or not two variables are same OWL individuals. Built-in atom is one of the most advanced features offered by SWRL because of its ability to support more complex predicates including common mathematical operations. Table 5.5 explains the meaning and function of each atom in exemplary SWRL rules implemented in this study.

Table 5.5 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)	

SWRL rule development

In OntoSCS system, SWRL rules are used to represent two types of criteria in structural design and sustainability assessment. The first one is mathematical equations. The equations in structural design regulation for calculating physical properties of structural member can be expressed alternatively as conditional statements in if-then form. For example, Equation 5.1 is used to calculate the ultimate axial load capacity of concrete column, in which the total load capacity equals the summation of concrete and reinforcement's load capacity.

Equation 5.1 Calculate the ultimate axial load capacity

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

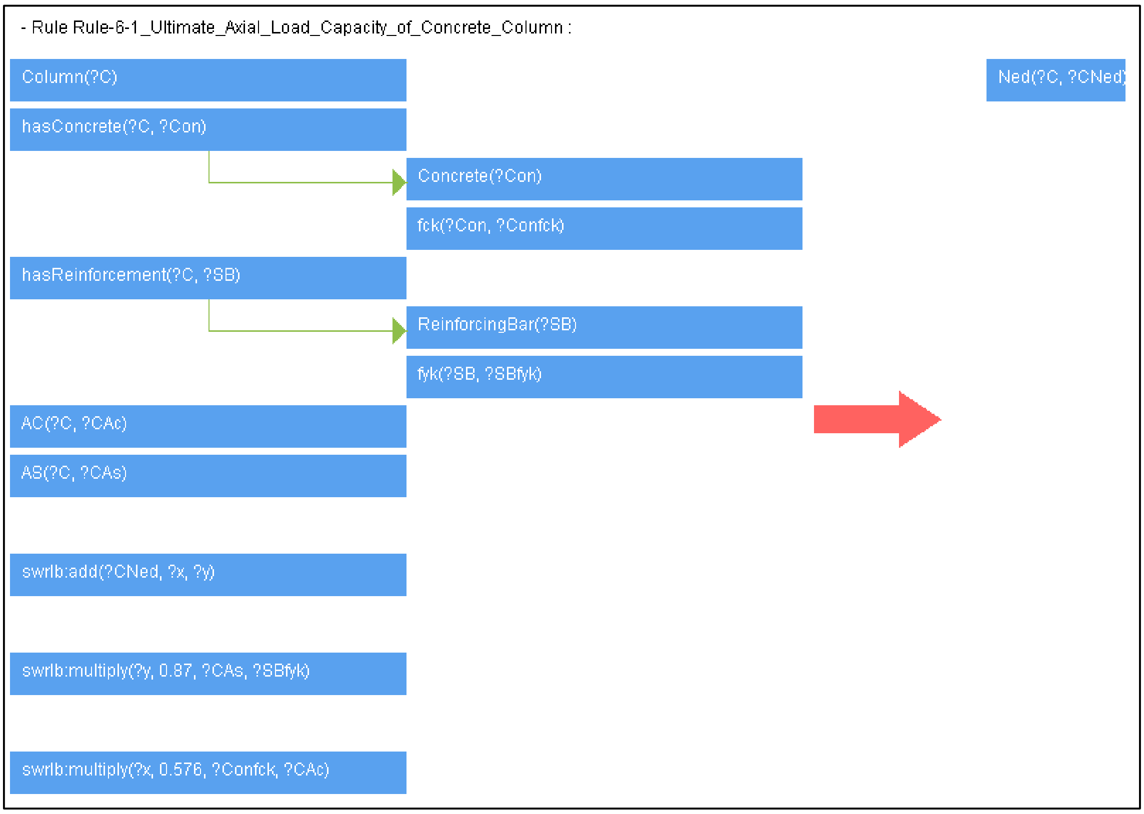
In conditional statements, this equation can be expresses as following if-then form:

If *Column has concrete and reinforcing bar*
and *Total area of the longitudinal reinforcement is* A_s
and *Total area of column cross-section is* A_c
and *Concrete has characteristic strength "*f_{ck}*"*
and *Reinforcing bar has characteristic yield strength "*f_{yk}*"*
and *"x" is multiplication of safety factor 0.567,* f_{ck} *and* A_c
and *"y" is multiplication of safety factor 0.87,* f_{yk} *and* A_s
and *"z" is summation of "x" and "y"*

Then *Column has ultimate axial load capacity "z"*

In general, the if-then rules can be understood as if the antecedent holds, then the consequent must also hold. Therefore, this if-then rule are represented using SWRL rule and SWRL built-ins *swrlb:multiply* and *swrlb:add*, as demonstrated in Rule 5-1. The antecedent and consequent in this rule is visualised in AxiomeTab of Protégé-OWL, as shown in Figure 5.12.

Rule 5-1 Calculating ultimate axial load capacity of concrete column
Column(?C) Λ AC(?C, ?CAc) Λ AS(?C, ?CAs) Λ hasConcrete(?C, ?Con) Λ Concrete(?Con) Λ fck(?Con, ?Confck) Λ hasReinforcement(?C, ?SB) Λ ReinforcingBar(?SB) Λ fyk(?SB, ?SBfyk) Λ swrlb:multiply(?x, 0.576, ?Confck, ?CAc) Λ *swrlb:multiply(?y, 0.87, ?CAs, ?SBfyk) Λ swrlb:add(?CNed, ?x, ?y) →* *Ned(?C, ?CNed)*



```
- Rule Rule-6-1_Ultimate_Axial_Load_Capacity_of_Concrete_Column :
Column(?C)
hasConcrete(?C, ?Con)
Concrete(?Con)
fck(?Con, ?Confck)
hasReinforcement(?C, ?SB)
ReinforcingBar(?SB)
fyk(?SB, ?SBfyk)
AC(?C, ?CAc)
AS(?C, ?CAs)
swrlb:add(?CNed, ?x, ?y)
swrlb:multiply(?y, 0.87, ?CAs, ?SBfyk)
swrlb:multiply(?x, 0.576, ?Confck, ?CAc)
Ned(?C, ?CNed)
```

Figure 5.12 Antecedent and consequent in Rule 5-1.

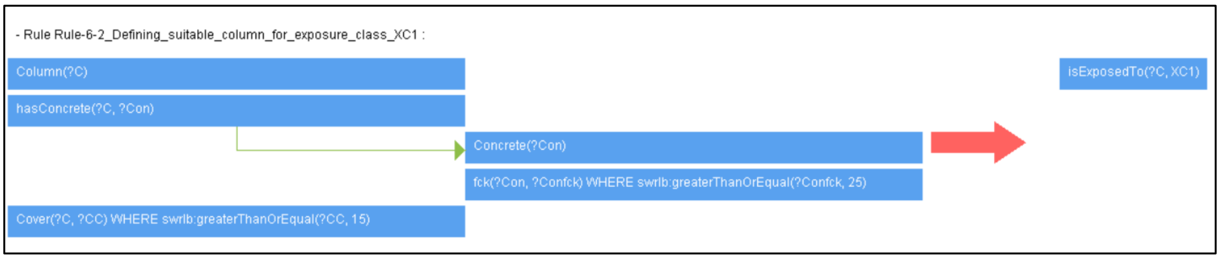
Similar approach can be adopted to convert equations used for determining the value of sustainable indicator such as embodied CO_2e. Rule 5-2 illustrates the calculation of total amount of embodied CO_2e in concrete column.

Rule 5-2 Calculate total embodied CO_2e

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

→ *TotalECO2e(?C,?TECO2)*

Rule 5-2 implies that the total embodied CO_2e (*TotalECO*$_2$*e*) 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 (*EmbodiedCO*$_2$*e*). The calculation is achieved using SWRL built-in *swrlb:multiply* as well. Figure 5.13 demonstrate the antecedent and consequent in Rule 5-2.



- Rule Rule-6-2_Defining_suitable_column_for_exposure_class_XC1 :

Column(?C)

hasConcrete(?C, ?Con)

Concrete(?Con)

fck(?Con, ?Confck) WHERE swrlb:greaterThanOrEqual(?Confck, 25)

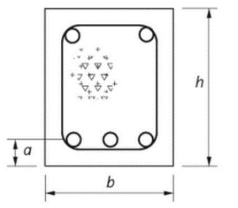
Cover(?C, ?CC) WHERE swrlb:greaterThanOrEqual(?CC, 15)

isExposedTo(?C, XC1)

Figure 5.13 Antecedent and consequent in Rule 5-2.

The second type of design criteria using SWRL to represent is non-calculation criteria. In structural design regulation, some requirements specified in design principles and application rules are not calculated from equations but obtained from practical assessment. For example, the fire resistance requirement governs the size of structural element and thickness of protection cover (concrete surface to main bar axis). In the case of concrete column, the permissible combinations of member dimensions and cover are given in Table 5.6.

Table 5.6 Minimum dimensions and covers for fire resistance.

Standard fire resistance (minutes)	***Minimum dimensions (mm)***		
	Column width b_{min}	*Cover*	
R60	200	25	
R90	300	25	
R120	350	35	

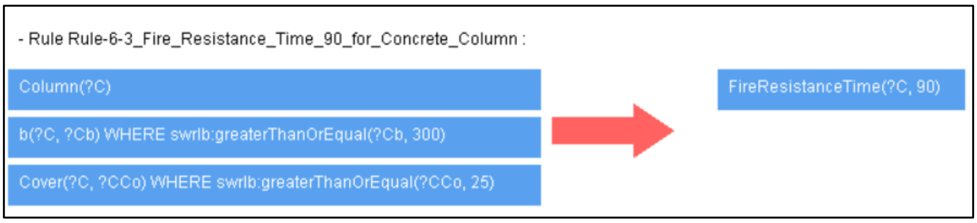
In this case, each fire resistance requirement for minimum dimension can be expressed as if-then rule, taking the R90 (90 minutes resistance) as an example:

If *Column has Width "b" that equals or is larger than "300mm"*
and *Column has Cover "a" that equals or is larger than "25mm"*

Then *Column has Fire Resistance Time "90 minutes"*

Therefore, this rule can be converted into SWRL Rule 5-3 in the same way as demonstrated in Rule 5-1. Built-in *swrlb:greaterThanOrEqual* is used in this rule to represent *"equals or is larger than"* requirements for dimension and cover. Figure 5.14 shows the antecedent and consequent of this rule.

Rule 5-3 Fire resistance time 90 minutes for concrete column
Column(?C) ∧ b(?C, ?Cb) ∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?Cb, 300) ∧ *swrlb:greaterThanOrEqual(?CCo, 25) →* *FireResistanceTime(?C, 90)*



- Rule Rule-6-3_Fire_Resistance_Time_90_for_Concrete_Column :

Column(?C)

b(?C, ?Cb) WHERE swrlb:greaterThanOrEqual(?Cb, 300)

Cover(?C, ?CCo) WHERE swrlb:greaterThanOrEqual(?CCo, 25)

FireResistanceTime(?C, 90)

Figure 5.14 Antecedent and consequent in Rule 5-3.

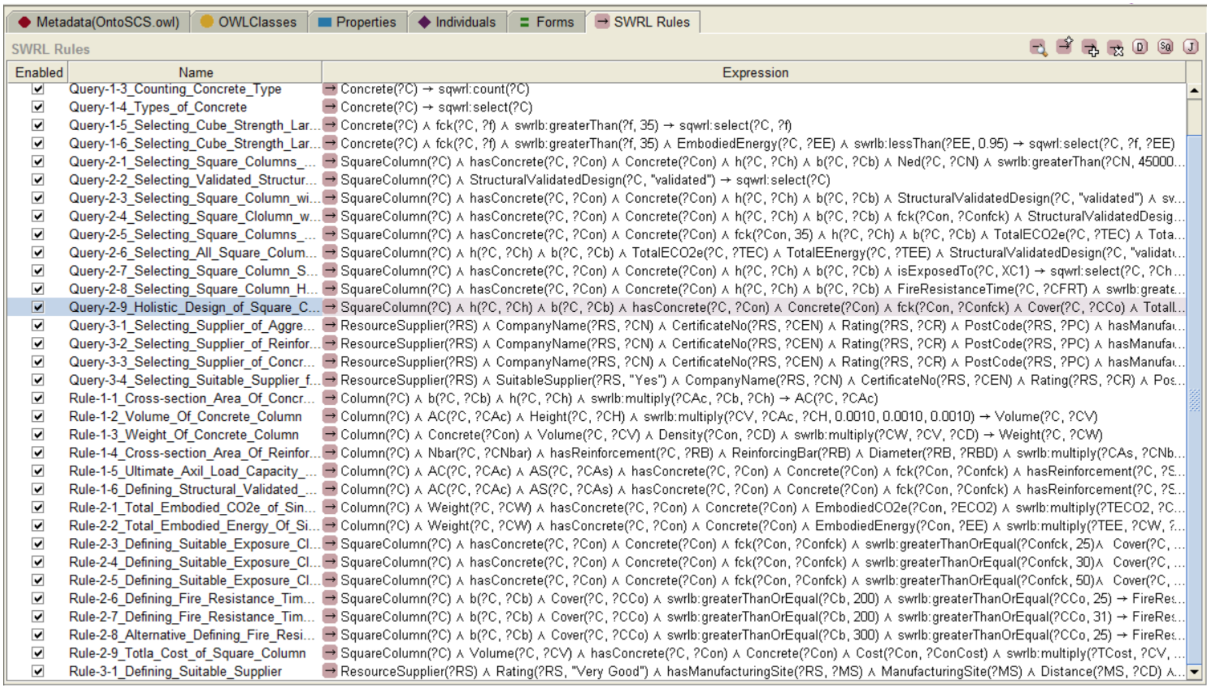
SQWRL query development

In addition to the SWRL rules, the development of SQWRL queries is equally important since it provides the capability to retrieve the facts either defined in the ontology or inferred by the SWRL rules. SQWRL takes the antecedent of SWRL and treats it as a specification for a query. The core built-in of SQWRL used as consequent is *sqwrl:select*. For instance, Query 5-1 presents a SQWRL query for select column with concrete strength class greater than C30.

Query 5-1 Select the concrete with strength class greater than C30
Column(?C) ∧ hasConcrete(?C,?Con) ∧ Concrete(?Con) ∧ fck(?Con,?Confck) ∧ swrlb:greaterThan(?Confck, 30) → sqwrl:select(?C,?Confck)

The meaning of Query 5-1 is if there is a column with concrete strength (f_{ck}) 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 following the same manner explained in this section. As shown in Figure 5.15, the rule set is incorporated into the OntoSCS prototype system for specific applications of case study in Chapter 6. Details of rules and queries edited in SWRLTab can be found in Appendix 2.



Enabled	Name	Expression
☑	Query-1-3_Counting_Concrete_Type	Concrete(?C) → sqwrl:count(?C)
☑	Query-1-4_Types_of_Concrete	Concrete(?C) → sqwrl:select(?C)
☑	Query-1-5_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C, ?f) ∧ swrlb:greaterThan(?f, 35) → sqwrl:select(?C, ?f)
☑	Query-1-6_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C, ?f) ∧ swrlb:greaterThan(?f, 35) ∧ EmbodiedEnergy(?C, ?EE) ∧ swrlb:lessThan(?EE, 0.95) → sqwrl:select(?C, ?f, ?EE)
☑	Query-2-1_Selecting_Square_Columns_...	SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ Ned(?C, ?CN) ∧ swrlb:greaterThan(?CN, 45000...
☑	Query-2-2_Selecting_Validated_Structur...	SquareColumn(?C) ∧ StructuralValidatedDesign(?C, "validated") → sqwrl:select(?C)
☑	Query-2-3_Selecting_Square_Column_wi...	SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ StructuralValidatedDesign(?C, "validated") ∧ sv...
☑	Query-2-4_Selecting_Square_Clolumn_w...	SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ fck(?Con, ?Confck) ∧ StructuralValidatedDesig...
☑	Query-2-5_Selecting_Square_Columns_...	SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, 35) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ TotalECO2e(?C, ?TEC) ∧ Tota...
☑	Query-2-6_Selecting_All_Square_Colum...	SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧ StructuralValidatedDesign(?C, "validat...
☑	Query-2-7_Selecting_Square_Column_S...	SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ isExposedTo(?C, XC1) → sqwrl:select(?C, ?Ch...
☑	Query-2-8_Selecting_Square_Column_H...	SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ FireResistanceTime(?C, ?CFRT) ∧ swrlb:greate...
☑	Query-2-9_Holistic_Design_of_Square_C...	SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ Cover(?C, ?CCo) ∧ TotalI...
☑	Query-3-1_Selecting_Supplier_of_Aggre...	ResourceSupplier(?RS) ∧ CompanyName(?RS, ?CN) ∧ CertificateNo(?RS, ?CEN) ∧ Rating(?RS, ?CR) ∧ PostCode(?RS, ?PC) ∧ hasManufa...
☑	Query-3-2_Selecting_Supplier_of_Reinfor...	ResourceSupplier(?RS) ∧ CompanyName(?RS, ?CN) ∧ CertificateNo(?RS, ?CEN) ∧ Rating(?RS, ?CR) ∧ PostCode(?RS, ?PC) ∧ hasManufa...
☑	Query-3-3_Selecting_Supplier_of_Concr...	ResourceSupplier(?RS) ∧ CompanyName(?RS, ?CN) ∧ CertificateNo(?RS, ?CEN) ∧ Rating(?RS, ?CR) ∧ PostCode(?RS, ?PC) ∧ hasManufa...
☑	Query-3-4_Selecting_Suitable_Supplier_f...	ResourceSupplier(?RS) ∧ SuitableSupplier(?RS, "Yes") ∧ CompanyName(?RS, ?CN) ∧ CertificateNo(?RS, ?CEN) ∧ Rating(?RS, ?CR) ∧ Pos...
☑	Rule-1-1_Cross-section_Area_Of_Concr...	Column(?C) ∧ b(?C, ?Cb) ∧ h(?C, ?Ch) ∧ swrlb:multiply(?CAc, ?Cb, ?Ch) → AC(?C, ?CAc)
☑	Rule-1-2_Volume_Of_Concrete_Column	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_Weight_Of_Concrete_Column	Column(?C) ∧ Concrete(?Con) ∧ Volume(?C, ?CV) ∧ Density(?Con, ?CD) ∧ swrlb:multiply(?CW, ?CV, ?CD) → Weight(?C, ?CW)
☑	Rule-1-4_Cross-section_Area_Of_Reinfor...	Column(?C) ∧ Nbar(?C, ?CNbar) ∧ hasReinforcement(?C, ?RB) ∧ ReinforcingBar(?RB) ∧ Diameter(?RB, ?RBD) ∧ swrlb:multiply(?CAs, ?CNb...
☑	Rule-1-5_Ultimate_Axil_Load_Capacity_...	Column(?C) ∧ AC(?C, ?CAc) ∧ AS(?C, ?CAs) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ hasReinforcement(?C, ?S...
☑	Rule-1-6_Defining_Structural_Validated_...	Column(?C) ∧ AC(?C, ?CAc) ∧ AS(?C, ?CAs) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ hasReinforcement(?C, ?S...
☑	Rule-2-1_Total_Embodied_CO2e_of_Sin...	Column(?C) ∧ Weight(?C, ?CW) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ EmbodiedCO2e(?Con, ?ECO2) ∧ swrlb:multiply(?TECO2, ?C...
☑	Rule-2-2_Total_Embodied_Energy_Of_Si...	Column(?C) ∧ Weight(?C, ?CW) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ EmbodiedEnergy(?Con, ?EE) ∧ swrlb:multiply(?TEE, ?CW, ?...
☑	Rule-2-3_Defining_Suitable_Exposure_Cl...	SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ swrlb:greaterThanOrEqual(?Confck, 25)∧ Cover(?C, ...
☑	Rule-2-4_Defining_Suitable_Exposure_Cl...	SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ swrlb:greaterThanOrEqual(?Confck, 30)∧ Cover(?C, ...
☑	Rule-2-5_Defining_Suitable_Exposure_Cl...	SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ swrlb:greaterThanOrEqual(?Confck, 50)∧ Cover(?C, ...
☑	Rule-2-6_Defining_Fire_Resistance_Tim...	SquareColumn(?C) ∧ b(?C, ?Cb) ∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?Cb, 200) ∧ swrlb:greaterThanOrEqual(?CCo, 25) → FireRes...
☑	Rule-2-7_Defining_Fire_Resistance_Tim...	SquareColumn(?C) ∧ b(?C, ?Cb) ∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?Cb, 200) ∧ swrlb:greaterThanOrEqual(?CCo, 31) → FireRes...
☑	Rule-2-8_Alternative_Defining_Fire_Resi...	SquareColumn(?C) ∧ b(?C, ?Cb) ∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?Cb, 300) ∧ swrlb:greaterThanOrEqual(?CCo, 25) → FireRes...
☑	Rule-2-9_Totla_Cost_of_Square_Column	SquareColumn(?C) ∧ Volume(?C, ?CV) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ Cost(?Con, ?ConCost) ∧ swrlb:multiply(?TCost, ?CV, ...
☑	Rule-3-1_Defining_Suitable_Supplier	ResourceSupplier(?RS) ∧ Rating(?RS, "Very Good") ∧ hasManufacturingSite(?RS, ?MS) ∧ ManufacturingSite(?MS) ∧ Distance(?MS, ?CD) ∧...

Figure 5.15 SWRL rules and SQWRL queries in OntoSCS ontology.

5.5 Summary

This chapter explained the procedures of implementing OntoSCS prototype system in software environment. Following methodological framework proposed in chapter 3, the implementation of system has been conducted in three stages: preparation, ontology development and rule development.

The preparation of OntoSCS ontology development includes the knowledge acquisition from literatures related to sustainable structural design. The main outcome of this stage is that all the important concepts are elicited and organised in taxonomic hierarchy. UML diagram is useful in this stage for representing the knowledge model.

The ontology development stage mainly consists of seven steps with adoption of the Ontology Development 101 methodology. The outcome of this stage is OntoSCS ontology without rules. Two validation activities are examined in order to verify the correctness and consistency of OntoSCS ontology. The first validation activity is semantically verifying the ontology. Manual validation approach is adopted by consulting domain experts and checking if the concepts in ontology has been correctly classified. It is an iterative process along the ontology development lifecycle. Semantic errors caused by imprecise defined classes are corrected during this process to ensure the correctness of ontology. The second validation activity is syntactic verification to make sure there are no anomalies in developed ontology. By using the Pellet reasoner in Protégé-OWL, the validation ensures the consistency of ontology. Like the semantic validation, the syntactic verification also needs to be conducted iteratively.

Taking advantage of SWRLTab plug-in of Protégé-OWL, the rule development has been completed by adding SWRL rules and SQWRL queries to the ontology for different applications. After the implementation of prototype system, it is important to validate whether the system is applicable for the design purpose. Chapter 6 will employ a case study validation to evaluate the effectiveness of prototype system.

Chapter 6 System Validation

In Chapter 5, the implementation of OntoSCS prototypical system in software environment has been explicitly explained. One of the main goal of this study is to investigate the Semantic Web technologies that can be used to develop a decision-support system for sustainable structural design. It focuses on integrating structural design knowledge and sustainability information in an ontology-based system. Therefore, this chapter employs a case study to test whether the prototypical system works as it was intended for and meaningful results can be drawn from the ontological knowledge base. Four structural design applications with different design criteria are demonstrated in this case study.

6.1 Case study description

A reinforced concrete column design case has been selected to validate the OntoSCS system and to demonstrate how this system works for sustainable structural design. There are three reasoning to choose concrete column design as case study. Firstly, among all the elements of a building, columns are one of the most crucial components that determine the structural feasibility. Hence, it is an appropriate example for illustrating that the OntoSCS is capable to provide feasible structural design solutions. Secondly, choosing concrete is because of the heavy use in the vast majority of construction projects over the world. In addition, 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. Apart from the load capacity, there are a number of more factors to consider for a sustainable concrete column, for instance, the amount of embodied energy and carbon, cost and fire resistance. Thus, the column design is good case to demonstrate a holistic approach for sustainable structural design using OntoSCS system. However, it is worthwhile to note that the methodology and procedures presented in this case study can be nonetheless applicable to other structural materials, components or forms.

A continuous reinforced concrete column of height $H = 4m$ with a rectangular cross section area bh, where b is the width and h is the length, is considered. The column is assumed to have an axial load of $N_u = 4500kN$. 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. Therefore, the design of concrete column is influenced by the following design considerations:

- The concrete column design must meet the requirement of structural feasibility, which means the column must have enough strength to support the loads transferred from the upper structure. To meet this requirement, the strength class of concrete used in the design, the number of reinforcement bars, type of reinforcement and the size of the column are the main factors to consider;
- The concrete column design must meet the requirement of durability in given exposure conditions;
- The concrete column design must meet the requirement of fire resistance;

- On the basis of structural feasibility, the sustainability of concrete column design could be considered. The embodied energy and carbon are used to evaluate the environmental aspect of sustainability and cost for economic aspect.

To conclude, there are five criteria to meet: structural feasibility, environmental impact (embodied energy and carbon), economic impact (cost), durability and fire safety. In the conventional structural design workflow as demonstrated in Figure 6.1, these five criteria are considered in two separated stages: structural design and sustainability evaluation. The main steps involved in conventional structural design process include:

1. Design requirement definition: including the specification of load capacity, durability and fire safety according to the types and performance requirements of the building. The design requirements are obtained by looking up the design regulations such as Eurocode by structural engineer;

2. Initial size assumption: the initial sizes of structural member are assumed by structural engineer based on the expert knowledge or/and experience of previous design project;

3. Manual calculation: detailed design of assumed structural member are calculated manually by structural engineer in accordance with design code such as Eurocode or design guide;

4. Structural analysis: design solutions are input into computer-aided structural analysis program to verify if the design meets the structural requirement including strength and stability;

5. Reinforcement detailing and scheduling;

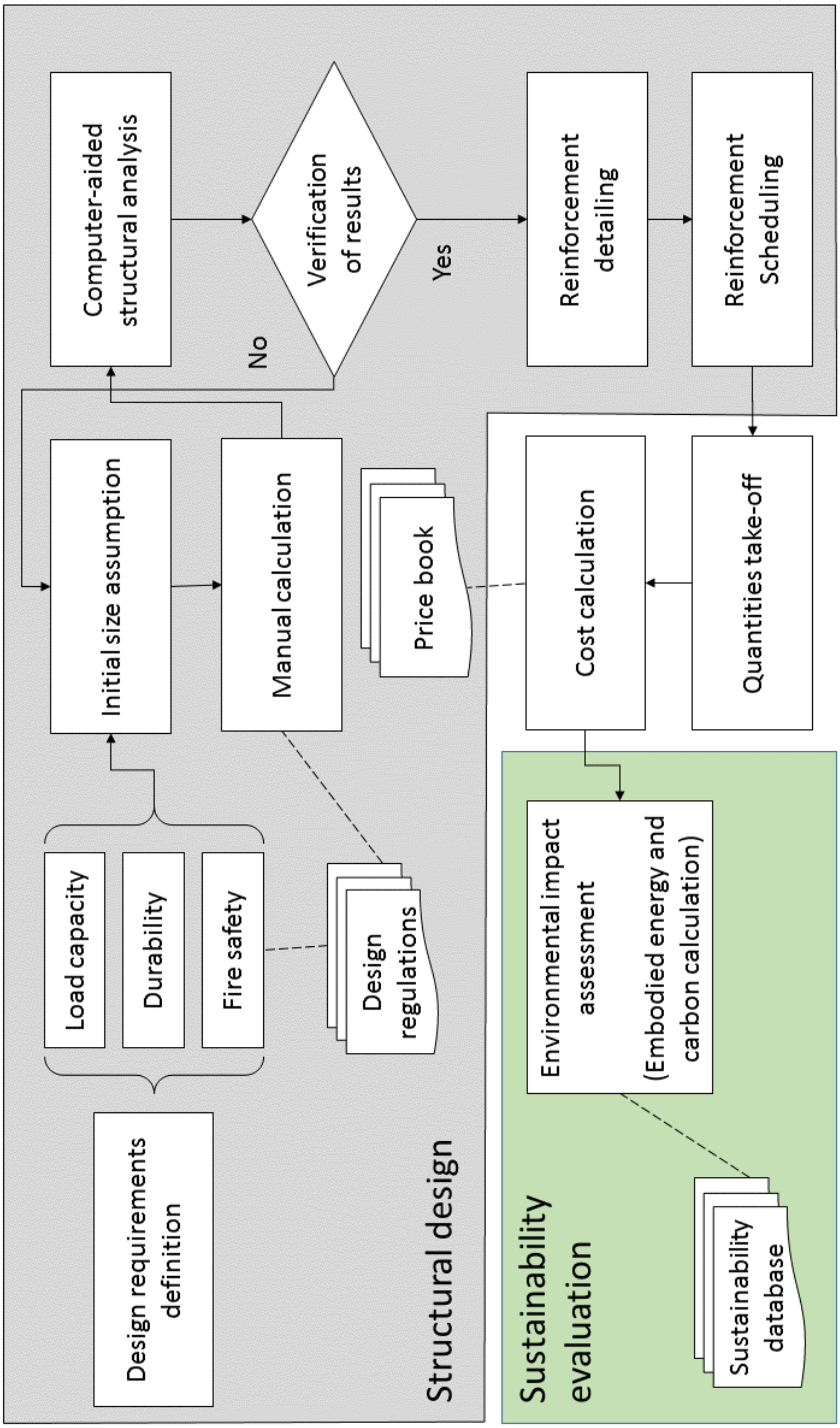


Figure 6.1 Conventional structural design workflow.

6. Cost calculation: the cost of structural frame and members are calculated in accordance with the construction price book;
7. Environmental impact assessment: embodied energy and carbon in structural member are calculated according to sustainability database and environmental assessment are carried out based on the completed structural design.

However, the conventional workflow has a number of drawbacks. Firstly, the initial sizes of structural members are assumed by structural engineer, which highly relies on the skill and experience. Iterative process is often required to find appropriate design solution. This process is time consuming and only one or two solutions are generated in common practice. Secondly, manual calculations of structural design, cost and environmental impact require structural engineer to take a large amount of time and energy to retrieve useful information from design codes, price books and databases. Additionally, it is difficult to avoid mistakes in manual calculation. Last but not least, the sustainability evaluation is carried out when the structural design is completed. This results in losing the opportunity to inform structural engineers about the environmental impact of their design solutions at initial design stage. Ideally, the sustainable factors such as embodied energy, carbon footprint and cost should be considered together with other structural design criteria at the first step of design workflow.

Therefore, the OntoSCS is implemented in this design case study to demonstrate how to overcome these drawbacks. In contrast to the conventional structural design workflow, Figure 6.2 illustrates a workflow using OntoSCS system in sustainable structural design. The main steps are concluded as follow:

1. Design requirement definition: identifying design requirements including structural load, exposure conditions, fire resistance time and sustainability target;

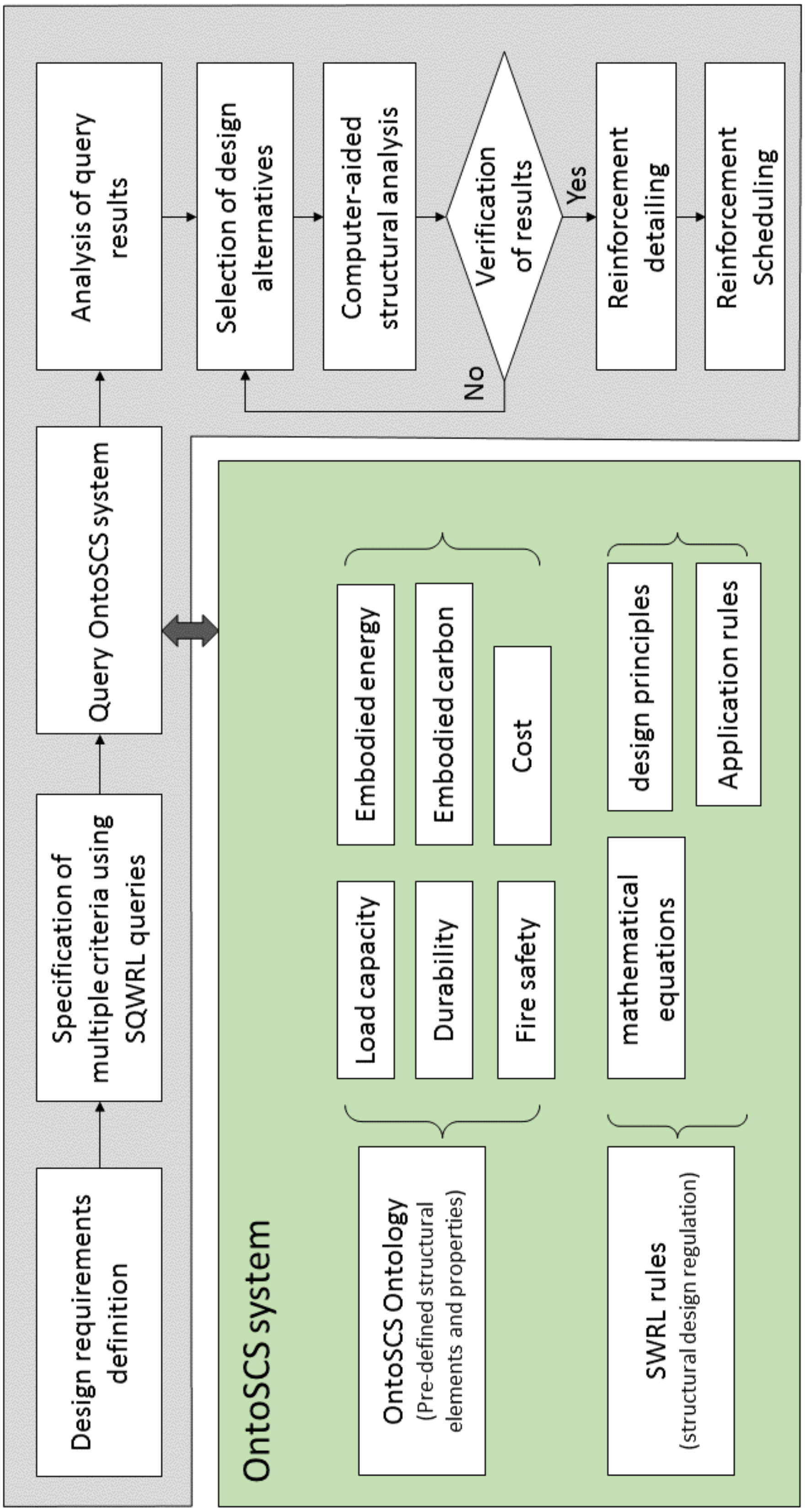


Figure 6.2 OntoSCS system embedded structural design workflow.

2. Specification of multiple criteria using SQWRL: the requirements identified in first step are defined as constraints in SQWRL queries;
3. Query OntoSCS system: structural engineer input various queries in OntoSCS system via SQWRLQueryTab according to different design scenarios;
4. Analysis of query results: based on the results of executing SQWRL queries, structural engineers obtain a selection of structural member design options from OntoSCS system. Since the selected options comply with structural feasibility, durability and fire safety requirements, the most sustainable structural design candidate can be determined by comparing the value of sustainability indicators (embodied energy and carbon, cost).

Comparing with the conventional structural design workflow, there is a number of advantages using OntoSCS in concrete design case. Firstly, as a remedy of inaccurate initial assumption of structural member sizes, a group of structural member candidates with a wide range of sizes is predefined in the ontology with associated physical properties, prices and sustainability indicator values of materials. Secondly, structural design compliances in regulation are converted into the SWRL rules, so that manual calculation is replaced by execution of SWRL rules in the OntoSCS system. Thus, all the selected design options comply with design code in the first place. Thirdly, the specification of multiple design criteria is represented as constraints in SQWRL queries. Structural engineer could interact with the system through raising different queries and obtain suitable design solution from results of queries. Overall, in this OntoSCS system embedded workflow, structural engineer is able to consider all five design criteria including structural feasibility, environmental impact (embodied energy and carbon), economic impact (cost), durability and fire safety from a holistic perspective. This makes it possible to minimise the environmental impact at the very beginning stage of design process and save time and effort for structural engineer to make contribution to sustainability of buildings. In the ensuing sections, details of how to implement and utilise OntoSCS system in reinforced concrete structural design will be presented.

6.2 Knowledge modelling of case study

Based on the analysis of the concrete structural design code, a group of design variables is identified to have influences on structural feasibility, durability, fire safety and sustainability of concrete column. In other words, these design variables could determine the essential characteristics of design outcomes: load capacity, suitable exposure classes, fire resistance time, cost, and amount of embodied energy and carbon. Figure 6.3 concludes the design variables including size, strength class of concrete, cement additions, addition proportion and protection cover. In addition, it provides the value range of each variable. For instance, the strength class of concrete used in column design could be selected from C25/30 to C40/50. Every connection between two variables represents a possible combination for a column design solution. Therefore, each path linking all five of the variables reveals a design alterative; for example, a column with size of 400×400mm^2, C28/35 concrete, 15% fly ash addition in concrete and 30mm cover. As shown in Figure 6.3, different combinations of variables lead to considerable amount of design alternatives, which exceed hundreds of times over the initial assumptions of column design proposed by structural engineer in conventional workflow. As a consequence, it is challenging for structural engineer to consider and calculate all these alternatives at initial design stage. Moreover, it is increasingly complicated while more variables are added and value range are extended. Therefore, by taking advantage of OntoSCS system's knowledge management and reasoning capabilities, column alternatives with design variables are modelled in the OntoSCS ontology as a knowledge repository for structural engineer to select. The reasoning and retrieval function offered by rules facilities this selecting process.

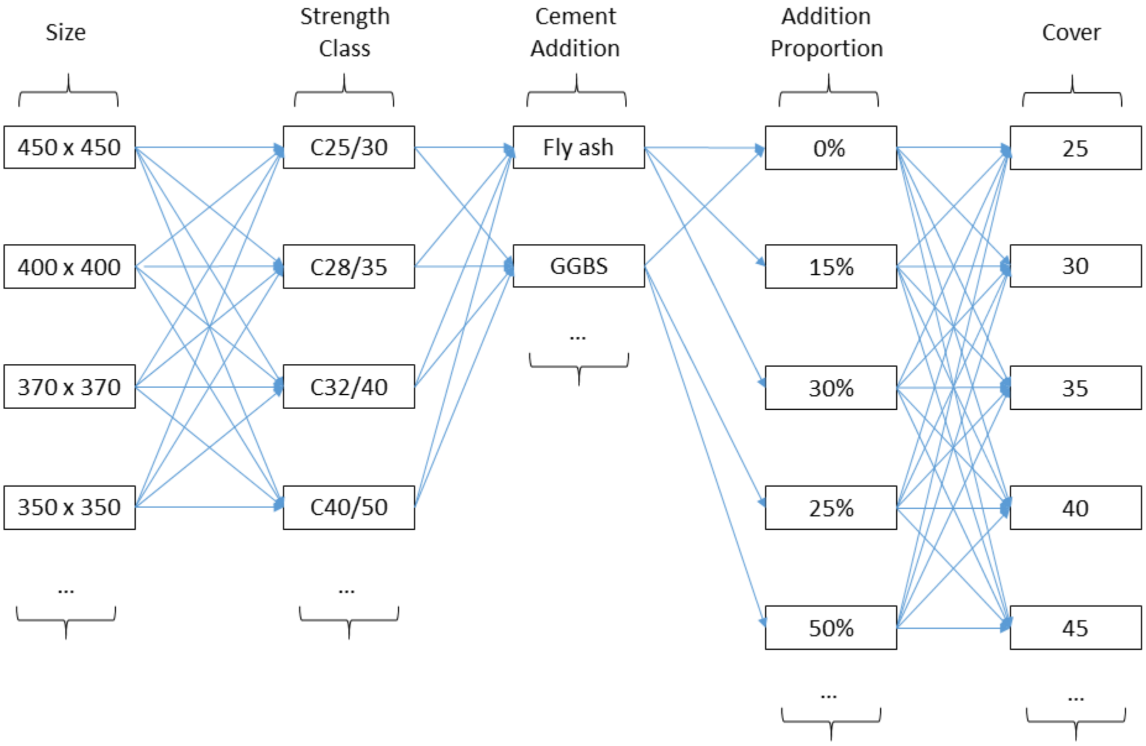


Figure 6.3 Design variables of concrete column.

In this case study, 50 square columns have been predefined as instances under the *Column* class, while 25 types of concrete with different strength classes and cement additions have been populated as instances of *Concrete* class in OntoSCS ontology. Each of the 50 square columns contains different type of concrete and has different structural dimensions. This fact is reflected in the OntoSCS ontology using datatype properties and object properties.

These design variables, which are the basic attributes of the column, are classified as initial facts. The initial facts include the width and length of the column *"b"* and *"h"*; the number of reinforcement bars "N_{bar}"; the diameter of reinforcement bas; the height of the column *"Height"*; and the types of concrete and reinforcement. The initial facts are manually edited into OntoSCS as object properties or data properties of instances. Other characteristics of concrete column are classified as inferred facts since they can be calculated on the basis of the initial facts using mathematical equations. For Example, the total area of the longitudinal reinforcement *“*A_s*”*, the total area of the cross-section of column *“*A_c*”* and total volume of the column need to be calculated during the design process. Then the following equations are applied for this purpose:

Equation 6.1 Calculation of the total area of the cross-section of column “A_c*”*

$$A_c = b \times h$$

Equation 6.2 Calculation of the total area of the longitudinal reinforcement “A_s*”*

$$A_s = \frac{D}{2} \times \frac{D}{2} \times \pi \times N_{bar}$$

Equation 6.3 Calculation of total volume of the column

$$Volume = A_c \times Height$$

Equation 6.4 Calculation of total weight of the column

$$Weight = desity \times volume$$

In OntoSCS ontology, the equations for calculating variables can be converted into SWRL rules using built-ins such as *swrlb:multiply*. Thus, the inference variables are not given specific values as they are deducted by the rules defined in ontology. The SWRL presentation of above examples are shown below:

Rule 6-1 The total area of the cross-section of column A_C

Column(?C) ∧ b(?C,?Cb) ∧ h(?C,?Ch) ∧ swrlb:multiply(?CAc,?Cb,?Ch)
→ AC(?C,?CAc)

Rule 6-2 The total area of the longitudinal reinforcement A_S

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 6-3 Calculating volume of concrete column

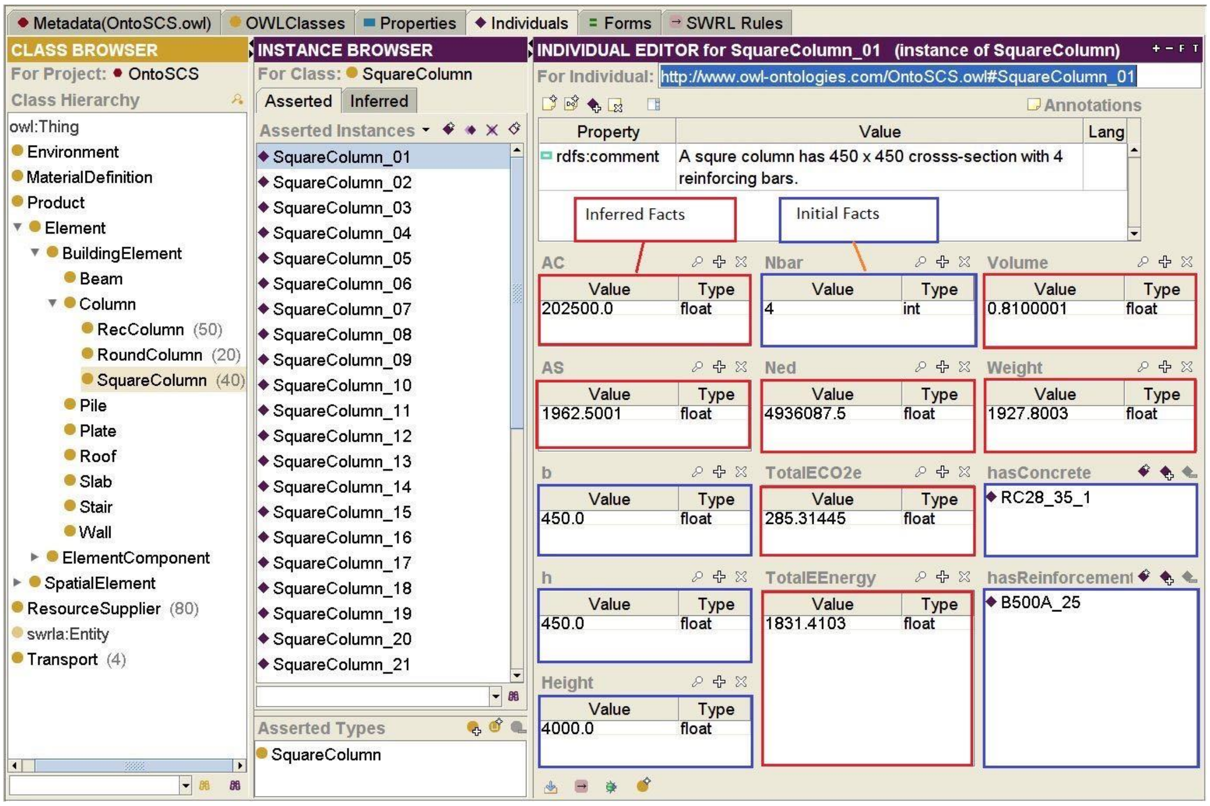
Column(?C) ∧ Ac(?C,?CAc) ∧ Height(?C,?CH) ∧ swrlb:multiply(?CV,?CAc,?CH, 0.0010, 0.0010, 0.0010)
→ Volume(?C,?CV)

Rule 6-4 Calculating weight of concrete column

Column(?C) ∧ Volume(?C,?CV) ∧ Density(?C,?CD) ∧ swrlb:multiply(?CW,?CV,?CD)
→ Weight(?C,?CW)

Based on initial facts defined in ontological knowledge base, the OntoSCS system infers new facts by executing rule set and populates new facts back into the ontology. Figure 6.4 takes one of the columns as an example to demonstrate the initial and inferred facts in different colour marks respectively.

The knowledge modelling of concrete column design case has been completed, which the knowledge concepts and corresponding objects in OntoSCS are presented in Figure 6.5. Every column alterative has been modelled as an ontology instance. Figure 6.6 shows a column instance *SquareColumn_02* and its relationships with other instances.



For Individual: http://www.owl-ontologies.com/OntoSCS.owl#SquareColumn_01

Property	Value	Lang
rdfs:comment	A squre column has 450 x 450 crosss-section with 4 reinforcing bars.	

Inferred Facts

Initial Facts

AC: Value 202500.0, Type float

Nbar: Value 4, Type int

Volume: Value 0.8100001, Type float

AS: Value 1962.5001, Type float

Ned: Value 4936087.5, Type float

Weight: Value 1927.8003, Type float

b: Value 450.0, Type float

TotalECO2e: Value 285.31445, Type float

hasConcrete: RC28_35_1

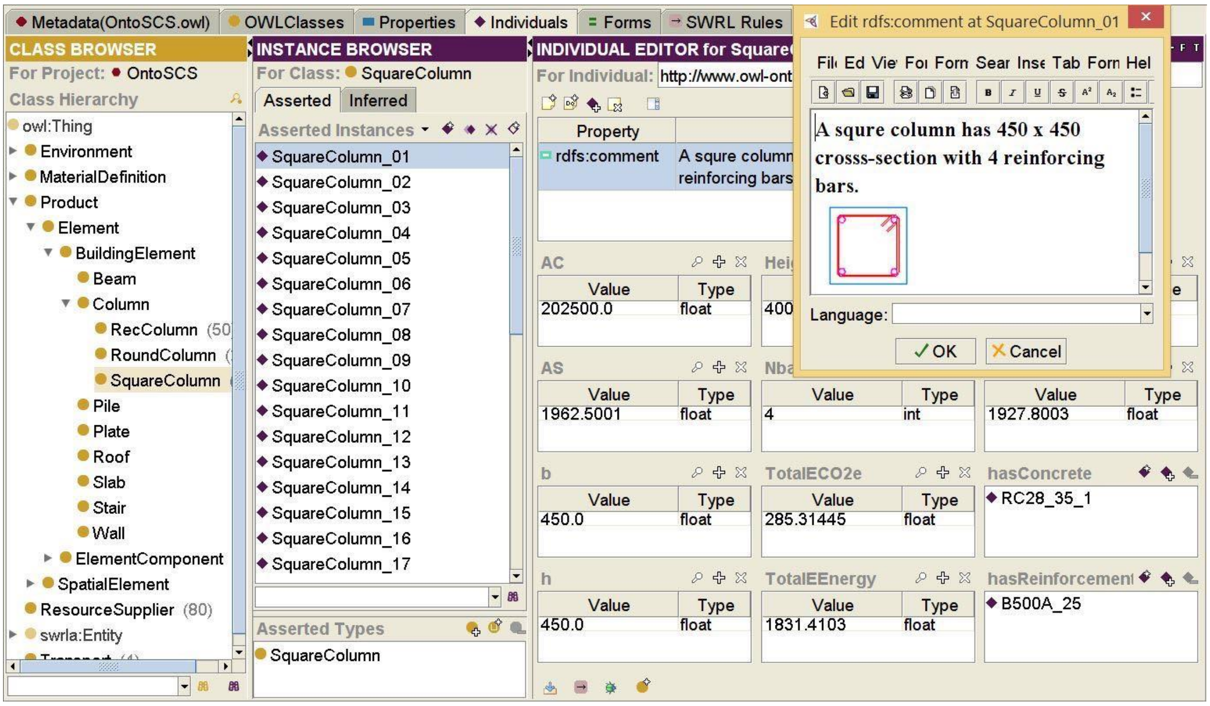
h: Value 450.0, Type float

TotalEEnergy: Value 1831.4103, Type float

hasReinforcement: B500A_25

Height: Value 4000.0, Type float

Figure 6.4 Initial facts and inferred facts in OntoSCS ontology.



For Individual: http://www.owl-ont

Property	Value
rdfs:comment	A squre column reinforcing bars

A squre column has 450 x 450 crosss-section with 4 reinforcing bars.

AC: Value 202500.0, Type float

AS: Value 1962.5001, Type float

Nbar: Value 4, Type int

Value 1927.8003, Type float

b: Value 450.0, Type float

TotalECO2e: Value 285.31445, Type float

hasConcrete: RC28_35_1

h: Value 450.0, Type float

TotalEEnergy: Value 1831.4103, Type float

hasReinforcement: B500A_25

Figure 6.5 Knowledge concepts of concrete column design case study.

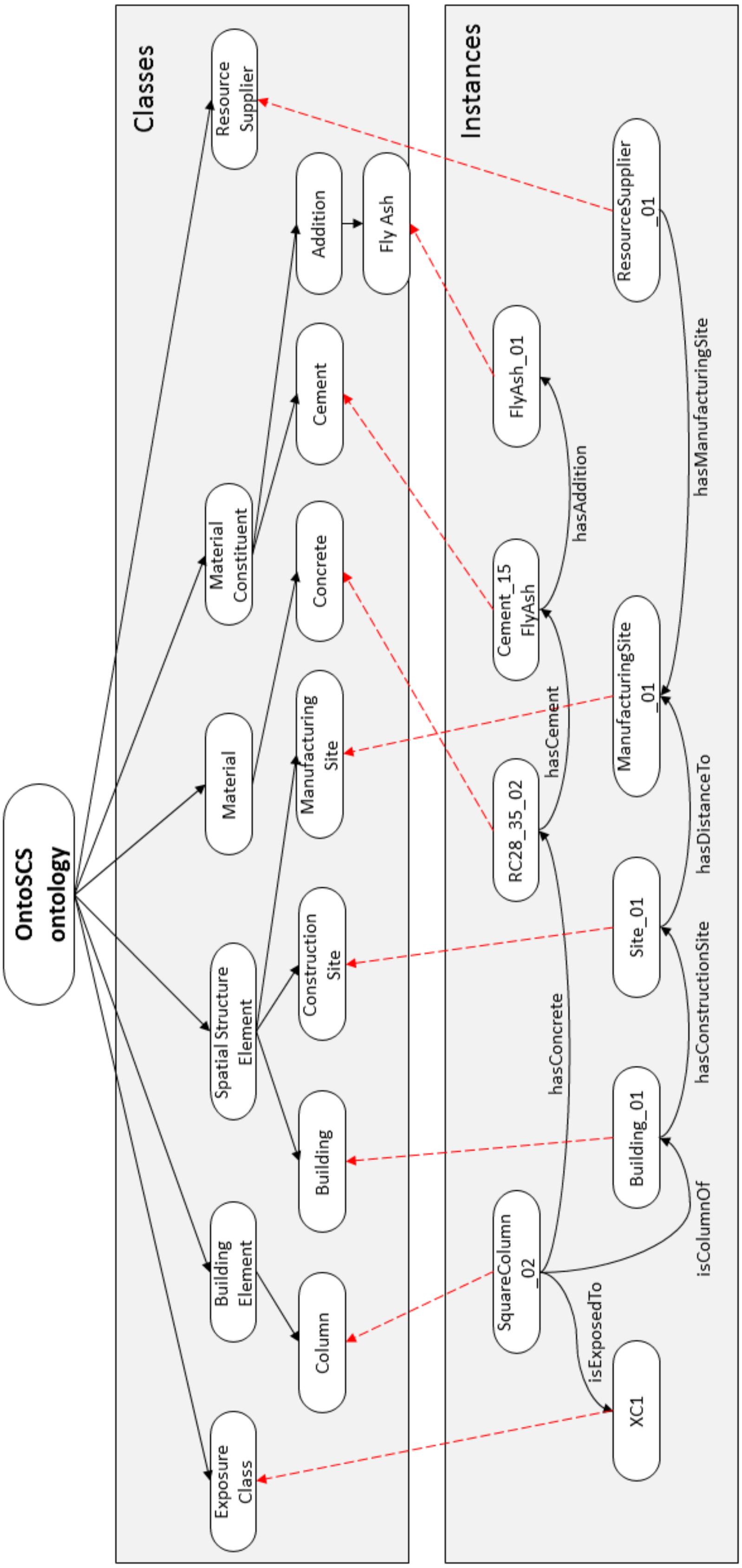


Figure 6.6 Example of instance in OntoSCS ontology for concrete column design.

In the ensuing section, a set of applications will be established based on the completed knowledge model of case study. In each application, queries and rules are exploited to test if the OntoSCS system could provide meaningful answers with regard to different design scenario in this case study. The correctness and efficiency of the query results would justify the reason of developing OntoSCS system.

6.3 Applications in case study

In this section, the applications are presented following an order of increasing complexity, from structural design with single consideration to holistic design with multiple objectives. The first application only focuses on structural feasibility of concrete column design. The second application adds sustainability, durability and fire safety considerations to the design case. A holistic design application is demonstrated by combining all the criteria applied in previous applications. The last application deals with the selection of structural material suppliers. SWRL rules and SQWRL queries as well as their built-ins are the essential Semantic Web technologies used in these applications.

6.3.1 Application 1 Structural design (single objective/ criterion)

6.3.1.1 Considering structural feasibility only

In this application, the structural feasibility is the only factor to consider for column design. To meet the requirement of structural feasibility, the first step is to determine the axial load capacity of all the candidate columns modelled in OntoSCS ontology. The axial load capacity of a reinforced concrete column is determined by two factors. One is the strength of concrete used for the column, while the other is the strength of the reinforcement. Thus, the ultimate axial load of a column could be calculated by combining the load capacities of concrete and reinforcement with respective safety factors applied on each. Equation 6.5 adopted for the calculation of axial load capacity is from reinforced concrete structural design manual to Eurocode 2.

Equation 6.5 Axial load capacity of reinforced concrete column.

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

In this application, Equation 6.5 is expressed using SWRL rules to determine the axial load capacity of all the square column instances in OntoSCS ontology, which is illustrated in Rule 6-5. The results of executing the rule are populated as new facets of datatype properties into square column instances.

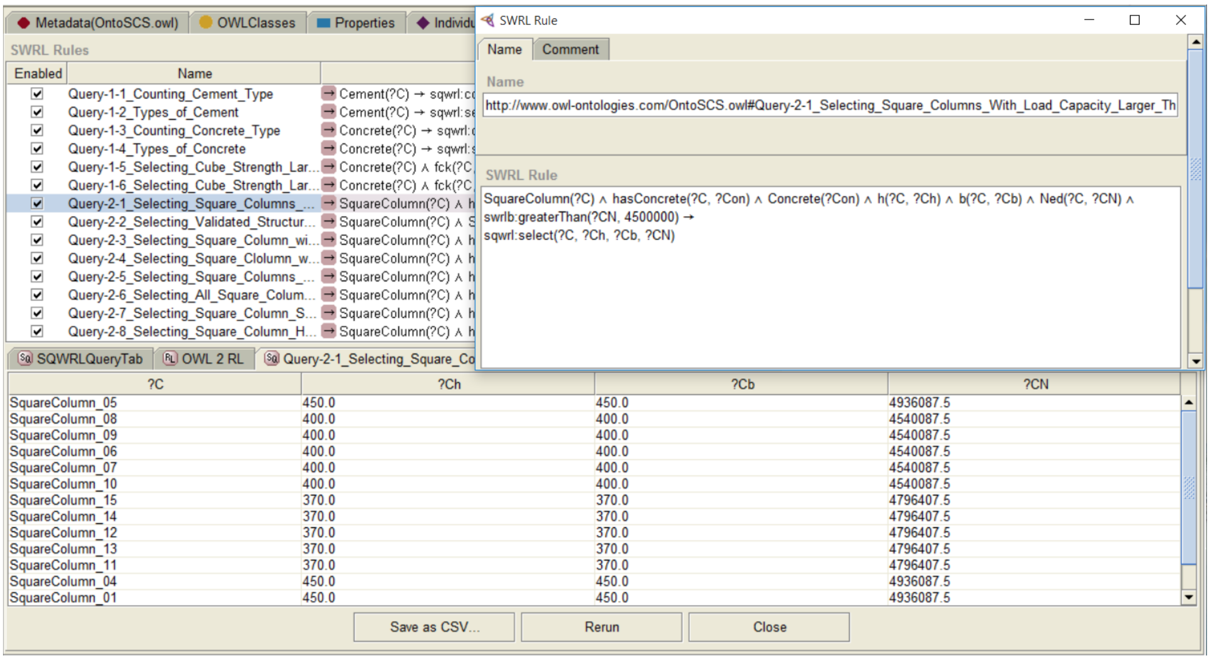
Rule 6-5. The ultimate axial load of a column
Column(?C) ∧ AC(?C,?CAc) ∧ AS(?C,?CAs) ∧ hasConcrete(?C,?Con) ∧ Concrete(?Con) ∧ fck(?Con,?Confck) ∧ hasReinforcement(?C,?SB) ∧ ReinforcingBar(?SB) ∧ fyk(?SB,?SBfyk) ∧ swrlb:multiply(?x, 0.576,?Confck,?CAc) ∧ swrlb:multiply(?y, 0.87,?CAs,?SBfyk) ∧ swrlb:add(?CNed,?x,?y) *→ Ned(?C,?CNed)*

The next step is to determine the constraint of selection. As the column is assumed to have an axial load of *Nu = 4500kN* in this case study, the value of axial load is taken as a constraint of structural feasibility. Any column that has load capacity equals or greater than *4500kN* is regarded as a feasible design solution. Therefore, the main aim is to select all the feasible columns from the OntoSCS ontology. This constraint of structural feasibility has been modelled using the SWRL built-in and is represented as *swrlb:greaterThanOrEqual(?x, 4500)*. The SQWRL query is formulated by adopting two built-ins of SWRL and SQWRL, *swrlb:greaterThanOrEqual* and *sqwrl:select* combined with other SWRL syntax. The output of executing Query 6-1 is presented in Figure 6.7.

Query 6-1 Selecting square columns with load capacity larger than 4500kN

SquareColumn(?C) ∧ hasConcrete(?C,?Con) ∧ Concrete(?Con) ∧ h(?C,?Ch) ∧ b(?C,?Cb) ∧ Ned(?C,?CNed) ∧ swrlb:greaterThanOrEqual(?CNed, 45,00,000)
→ sqwrl:select(?C,?Ch,?Cb,?CNed)

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.



Enabled	Name	
☑	Query-1-1_Counting_Cement_Type	Cement(?C) → sqwrl:c
☑	Query-1-2_Types_of_Cement	Cement(?C) → sqwrl:se
☑	Query-1-3_Counting_Concrete_Type	Concrete(?C) → sqwrl:
☑	Query-1-4_Types_of_Concrete	Concrete(?C) → sqwrl:
☑	Query-1-5_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C
☑	Query-1-6_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C
☑	Query-2-1_Selecting_Square_Columns_...	SquareColumn(?C) ∧ h
☑	Query-2-2_Selecting_Validated_Structur...	SquareColumn(?C) ∧ S
☑	Query-2-3_Selecting_Square_Column_wi...	SquareColumn(?C) ∧ h
☑	Query-2-4_Selecting_Square_Clolumn_w...	SquareColumn(?C) ∧ h
☑	Query-2-5_Selecting_Square_Columns_...	SquareColumn(?C) ∧ h
☑	Query-2-6_Selecting_All_Square_Colum...	SquareColumn(?C) ∧ h
☑	Query-2-7_Selecting_Square_Column_S...	SquareColumn(?C) ∧ h
☑	Query-2-8_Selecting_Square_Column_H...	SquareColumn(?C) ∧ h

Name: http://www.owl-ontologies.com/OntoSCS.owl#Query-2-1_Selecting_Square_Columns_With_Load_Capacity_Larger_Th

SWRL Rule:

```
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ Ned(?C, ?CN) ∧
swrlb:greaterThan(?CN, 4500000) →
sqwrl:select(?C, ?Ch, ?Cb, ?CN)
```

?C	?Ch	?Cb	?CN
SquareColumn_05	450.0	450.0	4936087.5
SquareColumn_08	400.0	400.0	4540087.5
SquareColumn_09	400.0	400.0	4540087.5
SquareColumn_06	400.0	400.0	4540087.5
SquareColumn_07	400.0	400.0	4540087.5
SquareColumn_10	400.0	400.0	4540087.5
SquareColumn_15	370.0	370.0	4796407.5
SquareColumn_14	370.0	370.0	4796407.5
SquareColumn_12	370.0	370.0	4796407.5
SquareColumn_13	370.0	370.0	4796407.5
SquareColumn_11	370.0	370.0	4796407.5
SquareColumn_04	450.0	450.0	4936087.5
SquareColumn_01	450.0	450.0	4936087.5

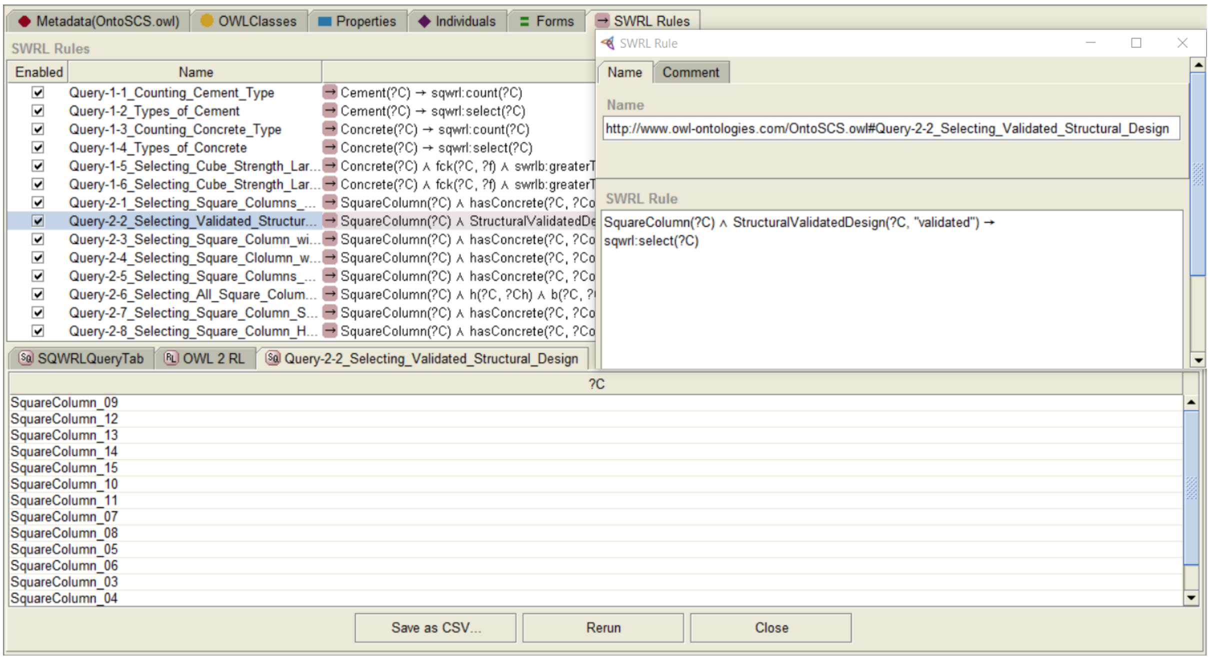
Figure 6.7 Execution and results of Query 6-1 for column selection.

Although the execution of Rule and Query manages to obtain appropriate results, it still cannot fulfil some more complicated design requirements due to its complexity. The shortcoming could be overcome by transferring the Rule 6-5 and Query 6-1 into the following forms in Rule 6-6 and Query 6-2. A new data-type property of the square column class is created called

StructuralValidatedDesign. Through executing Rule 6-6, square columns that meets structurally feasible requirement will be distinguished as validated design where the value of date-type property *StructuralValidatedDesign* is automatically defined as *"validated"* by the OntoSCS system. Therefore, the query rule could be simplified as shown in Query 6-2. The output of executing Query 6-2 in SQWRLQueryTab is shown in Figure 6.4, which is the same as results obtained in Figure 6.8.

Rule 6-6 Defining validated structural design
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) ∧ swrlb:greaterThanOrEqual(?CNed, 45,00,000) *→ StructuralValidatedDesign(?C, Yes)*

Query 6-2 Selecting validated structural design
StructuralValidatedDesign(?C, Yes) → sqwrl:select(?C)



Enabled	Name	
☑	Query-1-1_Counting_Cement_Type	Cement(?C) → sqwrl:count(?C)
☑	Query-1-2_Types_of_Cement	Cement(?C) → sqwrl:select(?C)
☑	Query-1-3_Counting_Concrete_Type	Concrete(?C) → sqwrl:count(?C)
☑	Query-1-4_Types_of_Concrete	Concrete(?C) → sqwrl:select(?C)
☑	Query-1-5_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C, ?f) ∧ swrlb:greaterT
☑	Query-1-6_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C, ?f) ∧ swrlb:greaterT
☑	Query-2-1_Selecting_Square_Columns_...	SquareColumn(?C) ∧ hasConcrete(?C, ?Co
☑	Query-2-2_Selecting_Validated_Structur...	SquareColumn(?C) ∧ StructuralValidatedDe
☑	Query-2-3_Selecting_Square_Column_wi...	SquareColumn(?C) ∧ hasConcrete(?C, ?Co
☑	Query-2-4_Selecting_Square_Clolumn_w...	SquareColumn(?C) ∧ hasConcrete(?C, ?Co
☑	Query-2-5_Selecting_Square_Columns_...	SquareColumn(?C) ∧ hasConcrete(?C, ?Co
☑	Query-2-6_Selecting_All_Square_Colum...	SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?
☑	Query-2-7_Selecting_Square_Column_S...	SquareColumn(?C) ∧ hasConcrete(?C, ?Co
☑	Query-2-8_Selecting_Square_Column_H...	SquareColumn(?C) ∧ hasConcrete(?C, ?Co

Name: http://www.owl-ontologies.com/OntoSCS.owl#Query-2-2_Selecting_Validated_Structural_Design

SWRL Rule: SquareColumn(?C) ∧ StructuralValidatedDesign(?C, "validated") → sqwrl:select(?C)

?C
SquareColumn_09
SquareColumn_12
SquareColumn_13
SquareColumn_14
SquareColumn_15
SquareColumn_10
SquareColumn_11
SquareColumn_07
SquareColumn_08
SquareColumn_05
SquareColumn_06
SquareColumn_03
SquareColumn_04

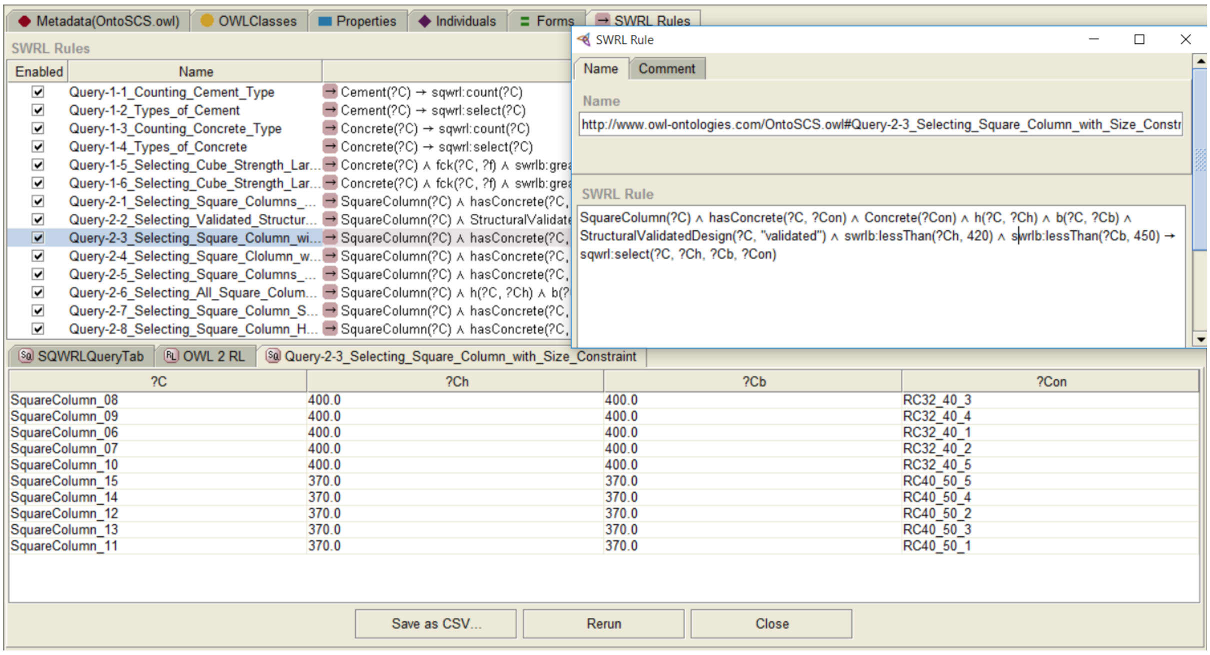
Figure 6.8 Execution and results of Query 6-2 for column selection.

6.3.1.2 *Structural design with size constraint*

The structural design always needs to meet the upstream requirements from architectural design. For example, the size of the column is often restricted under a given value for the purpose of architectural aesthetic or space utilisation. In this case, constraint of size can be applied in the query using SWRL built-in *swrlb:lessThan*. Query 6-3 illustrates the selection of concrete column with constraints of structural feasibility and column size less than *420×450mm*^{2}. The data-type property *StructuralValidatedDesign* defined in previous section is used in this query. The output of the executing the Query 6-3 in SQWRLQueryTab is shown in Figure 6.9.

Query 6-3 Selecting concrete column with size constraint

Column(?C) ∧ hasConcrete(?C,?Con) ∧ Concrete(?Con) ∧ h(?C,?Ch) ∧ b(?C,?Cb) ∧ StructuralValidatedDesign(?C, Yes) ∧ swrlb:lessThan(?Ch,420) ∧ swrlb:lessThan(?Cb, 450)
→ sqwrl:select(?C, ?Ch, ?Cb, ?Con)



Enabled	Name	
☑	Query-1-1_Counting_Cement_Type	Cement(?C) → sqwrl:count(?C)
☑	Query-1-2_Types_of_Cement	Cement(?C) → sqwrl:select(?C)
☑	Query-1-3_Counting_Concrete_Type	Concrete(?C) → sqwrl:count(?C)
☑	Query-1-4_Types_of_Concrete	Concrete(?C) → sqwrl:select(?C)
☑	Query-1-5_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C, ?f) ∧ swrlb:grea
☑	Query-1-6_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C, ?f) ∧ swrlb:grea
☑	Query-2-1_Selecting_Square_Columns_...	SquareColumn(?C) ∧ hasConcrete(?C,
☑	Query-2-2_Selecting_Validated_Structur...	SquareColumn(?C) ∧ StructuralValidate
☑	Query-2-3_Selecting_Square_Column_wi...	SquareColumn(?C) ∧ hasConcrete(?C,
☑	Query-2-4_Selecting_Square_Clolumn_w...	SquareColumn(?C) ∧ hasConcrete(?C,
☑	Query-2-5_Selecting_Square_Columns_...	SquareColumn(?C) ∧ hasConcrete(?C,
☑	Query-2-6_Selecting_All_Square_Colum...	SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?
☑	Query-2-7_Selecting_Square_Column_S...	SquareColumn(?C) ∧ hasConcrete(?C,
☑	Query-2-8_Selecting_Square_Column_H...	SquareColumn(?C) ∧ hasConcrete(?C,

Name

http://www.owl-ontologies.com/OntoSCS.owl#Query-2-3_Selecting_Square_Column_with_Size_Constr

SWRL Rule

```
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧
StructuralValidatedDesign(?C, "validated") ∧ swrlb:lessThan(?Ch, 420) ∧ swrlb:lessThan(?Cb, 450) →
sqwrl:select(?C, ?Ch, ?Cb, ?Con)
```

?C	?Ch	?Cb	?Con
SquareColumn_08	400.0	400.0	RC32_40_3
SquareColumn_09	400.0	400.0	RC32_40_4
SquareColumn_06	400.0	400.0	RC32_40_1
SquareColumn_07	400.0	400.0	RC32_40_2
SquareColumn_10	400.0	400.0	RC32_40_5
SquareColumn_15	370.0	370.0	RC40_50_5
SquareColumn_14	370.0	370.0	RC40_50_4
SquareColumn_12	370.0	370.0	RC40_50_2
SquareColumn_13	370.0	370.0	RC40_50_3
SquareColumn_11	370.0	370.0	RC40_50_1

Figure 6.9 Execution and results of Query 6-3 for column selection with size constraint.

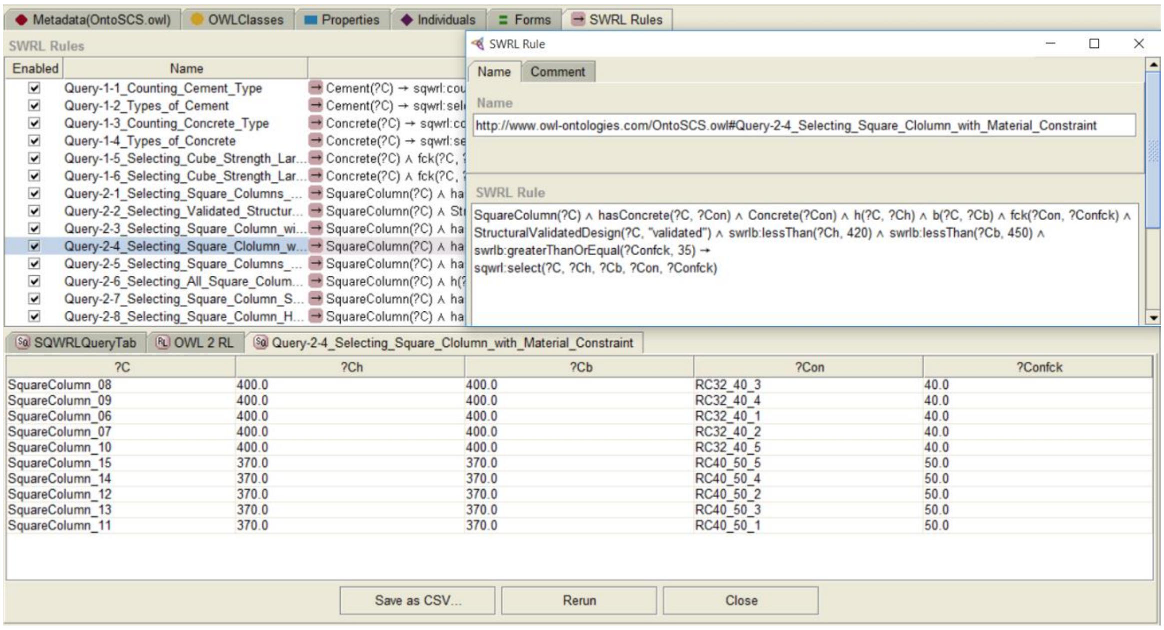
6.3.1.3 Structural design with material constraint

Other than the size constraint, the structural column design sometimes is required to use specific type of concrete. In this case, the strength class of concrete becomes a constraint while making the selection decisions. This section demonstrates an example that the constrains of dimension of column and concrete grade have been determined up front in addition to the initial constraint axial load of *Nu = 4500kN*. The constraint of concrete grade *"greater than C35"* is applied using SWRL built-in *swrlb:greaterThanOrEqual*. The Query 6-4 means any column validated for this design case in OntoSCS is selected if the dimension of the column is less than *420×450mm*^{2} and concrete strength class is higher than 35. The output is shown in Figure 6.10.

Query 6-4 Selecting concrete column with size and material constraint

Column(?C) ∧ h(?C,?Ch) ∧ b(?C,?Cb) ∧ hasConcrete(?C,?Con) ∧ Concrete(?Con) ∧ fck(?Con,?Confck) ∧ StructuralValidatedDesign(?C, Yes) ∧ swrlb:lessThan(?Ch, 450) ∧ swrlb:lessThan(?Cb, 450) ∧ swrlb:greaterThanOrEqual(?Confck, 35)

→ sqwrl:select(?C, ?Ch, ?Cb, ?Con, ?Confck)



Enabled	Name	
☑	Query-1-1_Counting_Cement_Type	Cement(?C) → sqwrl:cou
☑	Query-1-2_Types_of_Cement	Cement(?C) → sqwrl:sel
☑	Query-1-3_Counting_Concrete_Type	Concrete(?C) → sqwrl:co
☑	Query-1-4_Types_of_Concrete	Concrete(?C) → sqwrl:se
☑	Query-1-5_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C,
☑	Query-1-6_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?C,
☑	Query-2-1_Selecting_Square_Columns_...	SquareColumn(?C) ∧ ha
☑	Query-2-2_Selecting_Validated_Structur...	SquareColumn(?C) ∧ St
☑	Query-2-3_Selecting_Square_Column_wi...	SquareColumn(?C) ∧ ha
☑	Query-2-4_Selecting_Square_Clolumn_w...	SquareColumn(?C) ∧ ha
☑	Query-2-5_Selecting_Square_Columns_...	SquareColumn(?C) ∧ ha
☑	Query-2-6_Selecting_All_Square_Colum...	SquareColumn(?C) ∧ h(?
☑	Query-2-7_Selecting_Square_Column_S...	SquareColumn(?C) ∧ ha
☑	Query-2-8_Selecting_Square_Column_H...	SquareColumn(?C) ∧ ha

Name

http://www.owl-ontologies.com/OntoSCS.owl#Query-2-4_Selecting_Square_Clolumn_with_Material_Constraint

SWRL Rule

```
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ fck(?Con, ?Confck) ∧
StructuralValidatedDesign(?C, "validated") ∧ swrlb:lessThan(?Ch, 420) ∧ swrlb:lessThan(?Cb, 450) ∧
swrlb:greaterThanOrEqual(?Confck, 35) →
sqwrl:select(?C, ?Ch, ?Cb, ?Con, ?Confck)
```

?C	?Ch	?Cb	?Con	?Confck
SquareColumn_08	400.0	400.0	RC32_40_3	40.0
SquareColumn_09	400.0	400.0	RC32_40_4	40.0
SquareColumn_06	400.0	400.0	RC32_40_1	40.0
SquareColumn_07	400.0	400.0	RC32_40_2	40.0
SquareColumn_10	400.0	400.0	RC32_40_5	40.0
SquareColumn_15	370.0	370.0	RC40_50_5	50.0
SquareColumn_14	370.0	370.0	RC40_50_4	50.0
SquareColumn_12	370.0	370.0	RC40_50_2	50.0
SquareColumn_13	370.0	370.0	RC40_50_3	50.0
SquareColumn_11	370.0	370.0	RC40_50_1	50.0

Figure 6.10 Execution and results of Query 6-4 for column selection.

6.3.2 Application 2 Structural design considering sustainability

To achieve sustainable structural design, the environmental impact of structural member needs to be considered. In this case, embodied energy and carbon are the indicators used to evaluate the sustainability of concrete columns. The initial value of embodied energy and carbon have been manually edited as data-type property of concrete materials. Therefore, the total amount of embodied energy and carbon in each column needs to be calculated for comparison between all candidates, where the one with minimum embodied energy and carbon is regarded as the most sustainable design solution. In terms of the economic aspect of sustainability, the total cost of the column is used. The total cost and amount of embodied energy and carbon associated with column could be calculated through following equations:

Equation 6.6 The total embodied energy of the column.

$$\textit{Total Embodied Energy} = \textit{Weight} \times \textit{Embodied Energy per unit}$$

Equation 6.7 The total embodied carbon of the column.

$$\textit{Total Embodied } CO_2e = \textit{Weight} \times \textit{Embodied } CO_2e \textit{ per unit}$$

Equation 6.8 The total cost of the column.

$$\textit{Total Cost} = \textit{Volume} \times \textit{Cost per unit}$$

Equation 6.6 – 6.8 have been converted into the form of semantic rules, as shown in Rule 6-7, 6-8, and 6-9.

Rule 6-7 The total embodied energy of the column

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

Rule 6-8 The total embodied carbon of the column

Column(?C) ∧ Weight(?C,?CW) ∧ hasConcrete(?C,?Con) ∧ Concrete(?Con) ∧ EmbodiedCO2e(?Con,?ECO2) ∧ swrlb:multiply(?TECO2,?CW,?ECO2)
→ TotalECO2 e(?C,?TECO2)

Rule 6-9 The total cost of the column

Column(?C) ∧ Volume(?C,?CV) ∧ hasConcrete(?C,?Con) ∧ Concrete(?Con) ∧
UnitCost(?Con,?ConUC) ∧ swrlb:multiply(?TC,?CV,?ConUC)
→ TotalCost(?C,?TC)

In this application, like the real-world design practice, the dimensions of column and concrete type have been assumed up front, which are *450×450mm*^{2} and *RC28/35* respectively. A group of candidate column instances is selected from the OntoSCS ontology. After a comparison of all candidates, the one with minimum embodied energy and carbon is regarded as the most sustainable design solution.

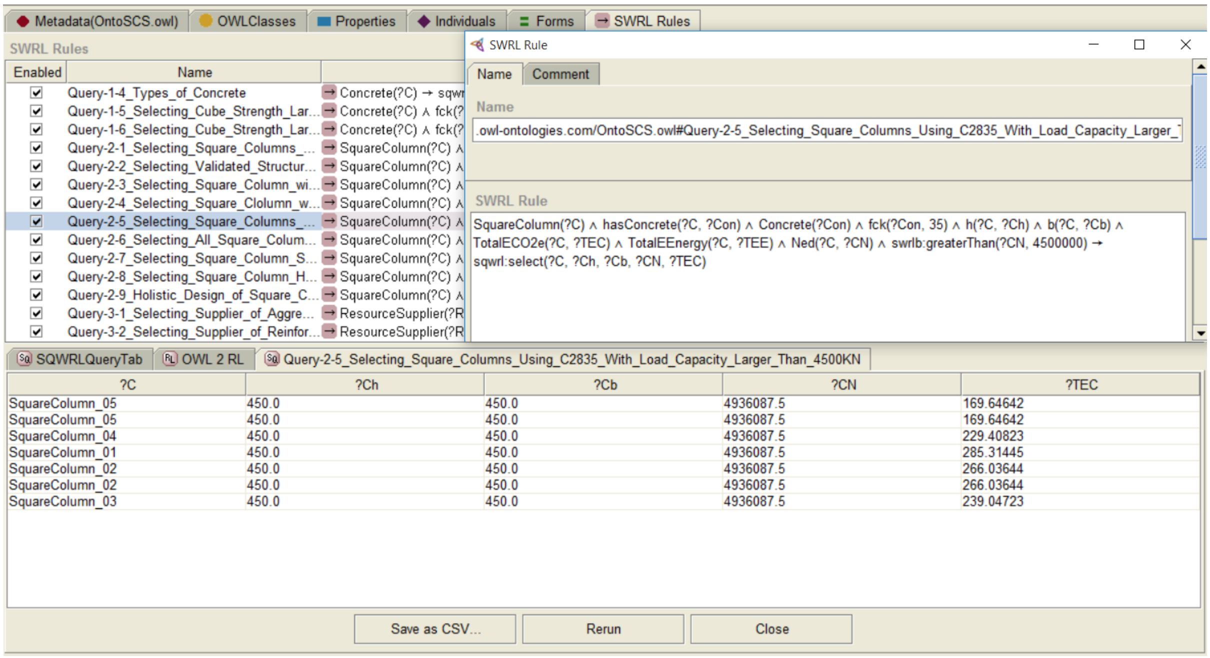
Query 6-5 Selecting column with consideration of sustainability

SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, 35) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧ StructuralValidatedDesign(?C, "validated")
→ sqwrl:select(?C, ?Ch, ?Cb, ?TEE, ?TEC)

Figure 6.11 demonstrates the execution and results in SQWRLQueryTab. The outputs from OntoSCS ontology are presented and compared in Table 6.1, which five 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.

Table 6.1 Comparison of selected columns.

Column No.	***Addition Proportion***	***Dimension (mm)***	***Strength Class***	***Axial Load (kN)***	***Embodied Energy (MJ)***	***Embodied Carbon (kgCO$_2$e)***
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



Enabled	Name	
☑	Query-1-4_Types_of_Concrete	Concrete(?C) → sqwr
☑	Query-1-5_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?
☑	Query-1-6_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?
☑	Query-2-1_Selecting_Square_Columns_...	SquareColumn(?C) ∧
☑	Query-2-2_Selecting_Validated_Structur...	SquareColumn(?C) ∧
☑	Query-2-3_Selecting_Square_Column_wi...	SquareColumn(?C) ∧
☑	Query-2-4_Selecting_Square_Clolumn_w...	SquareColumn(?C) ∧
☑	Query-2-5_Selecting_Square_Columns_...	SquareColumn(?C) ∧
☑	Query-2-6_Selecting_All_Square_Colum...	SquareColumn(?C) ∧
☑	Query-2-7_Selecting_Square_Column_S...	SquareColumn(?C) ∧
☑	Query-2-8_Selecting_Square_Column_H...	SquareColumn(?C) ∧
☑	Query-2-9_Holistic_Design_of_Square_C...	SquareColumn(?C) ∧
☑	Query-3-1_Selecting_Supplier_of_Aggre...	ResourceSupplier(?R
☑	Query-3-2_Selecting_Supplier_of_Reinfor...	ResourceSupplier(?R

Name: .owl-ontologies.com/OntoSCS.owl#Query-2-5_Selecting_Square_Columns_Using_C2835_With_Load_Capacity_Larger_

SWRL Rule:

```
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, 35) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧
TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧ Ned(?C, ?CN) ∧ swrlb:greaterThan(?CN, 4500000) →
sqwrl:select(?C, ?Ch, ?Cb, ?CN, ?TEC)
```

Query-2-5_Selecting_Square_Columns_Using_C2835_With_Load_Capacity_Larger_Than_4500KN

```
?C               ?Ch     ?Cb     ?CN         ?TEC
SquareColumn_05  450.0   450.0   4936087.5   169.64642
SquareColumn_05  450.0   450.0   4936087.5   169.64642
SquareColumn_04  450.0   450.0   4936087.5   229.40823
SquareColumn_01  450.0   450.0   4936087.5   285.31445
SquareColumn_02  450.0   450.0   4936087.5   266.03644
SquareColumn_02  450.0   450.0   4936087.5   266.03644
SquareColumn_03  450.0   450.0   4936087.5   239.04723
```

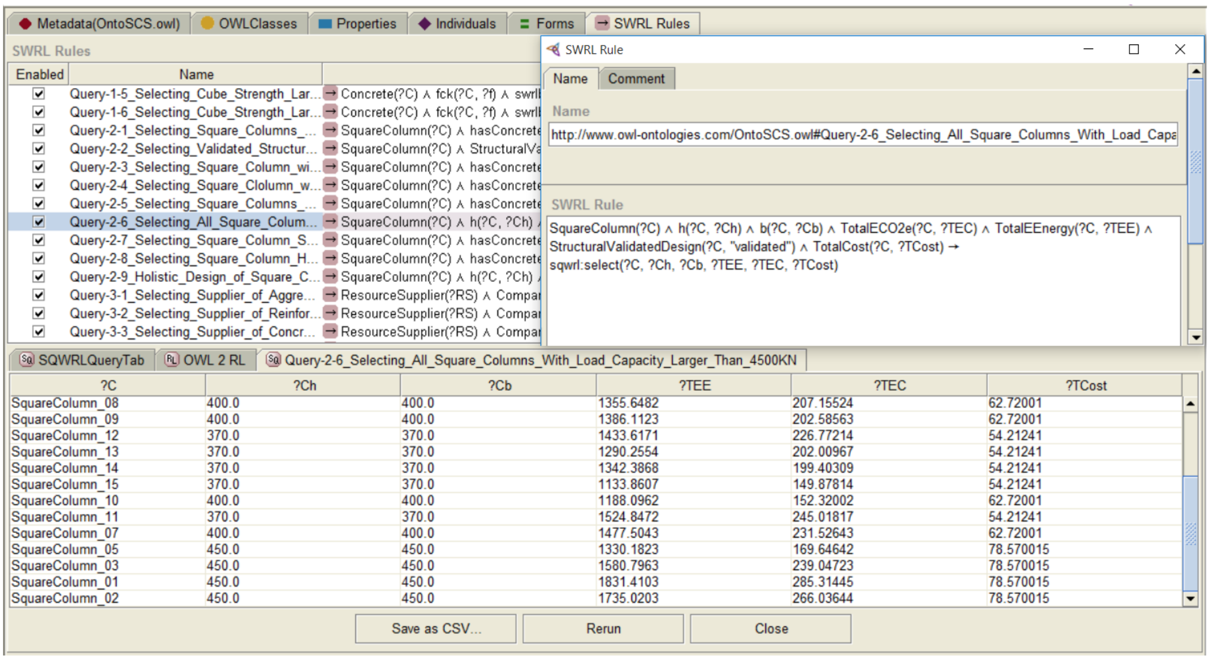
Figure 6.11 Execution and results of Query 6-5 for column selection.

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 example.

In this example, 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 6-6, all the columns with axial load capacity that is larger than *4500kN* are selected. The output of executing Query 6-6 is presented in Figure 6.12 and the results are compared in Table 6.2.

Query 6-6 Selecting column with consideration of sustainability

SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧ StructuralValidatedDesign(?C, "validated") ∧
TotalCost(?C, ?TCost)
→ sqwrl:select(?C, ?Ch, ?Cb, ?TEE, ?TEC, ?TCost)



Enabled	Name	
☑	Query-1-5_Selecting_Cube_Strength_Lar...	→ Concrete(?C) ∧ fck(?C, ?f) ∧ swrlb
☑	Query-1-6_Selecting_Cube_Strength_Lar...	→ Concrete(?C) ∧ fck(?C, ?f) ∧ swrlb
☑	Query-2-1_Selecting_Square_Columns_...	→ SquareColumn(?C) ∧ hasConcrete
☑	Query-2-2_Selecting_Validated_Structur...	→ SquareColumn(?C) ∧ StructuralVa
☑	Query-2-3_Selecting_Square_Column_wi...	→ SquareColumn(?C) ∧ hasConcrete
☑	Query-2-4_Selecting_Square_Clolumn_w...	→ SquareColumn(?C) ∧ hasConcrete
☑	Query-2-5_Selecting_Square_Columns_...	→ SquareColumn(?C) ∧ hasConcrete
☑	Query-2-6_Selecting_All_Square_Colum...	→ SquareColumn(?C) ∧ h(?C, ?Ch) ∧
☑	Query-2-7_Selecting_Square_Column_S...	→ SquareColumn(?C) ∧ hasConcrete
☑	Query-2-8_Selecting_Square_Column_H...	→ SquareColumn(?C) ∧ hasConcrete
☑	Query-2-9_Holistic_Design_of_Square_C...	→ SquareColumn(?C) ∧ h(?C, ?Ch) ∧
☑	Query-3-1_Selecting_Supplier_of_Aggre...	→ ResourceSupplier(?RS) ∧ Compar
☑	Query-3-2_Selecting_Supplier_of_Reinfor...	→ ResourceSupplier(?RS) ∧ Compar
☑	Query-3-3_Selecting_Supplier_of_Concr...	→ ResourceSupplier(?RS) ∧ Compar

Name
http://www.owl-ontologies.com/OntoSCS.owl#Query-2-6_Selecting_All_Square_Columns_With_Load_Capa

SWRL Rule
SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧
StructuralValidatedDesign(?C, "validated") ∧ TotalCost(?C, ?TCost) →
sqwrl:select(?C, ?Ch, ?Cb, ?TEE, ?TEC, ?TCost)

?C	?Ch	?Cb	?TEE	?TEC	?TCost
SquareColumn_08	400.0	400.0	1355.6482	207.15524	62.72001
SquareColumn_09	400.0	400.0	1386.1123	202.58563	62.72001
SquareColumn_12	370.0	370.0	1433.6171	226.77214	54.21241
SquareColumn_13	370.0	370.0	1290.2554	202.00967	54.21241
SquareColumn_14	370.0	370.0	1342.3868	199.40309	54.21241
SquareColumn_15	370.0	370.0	1133.8607	149.87814	54.21241
SquareColumn_10	400.0	400.0	1188.0962	152.32002	62.72001
SquareColumn_11	370.0	370.0	1524.8472	245.01817	54.21241
SquareColumn_07	400.0	400.0	1477.5043	231.52643	62.72001
SquareColumn_05	450.0	450.0	1330.1823	169.64642	78.570015
SquareColumn_03	450.0	450.0	1580.7963	239.04723	78.570015
SquareColumn_01	450.0	450.0	1831.4103	285.31445	78.570015
SquareColumn_02	450.0	450.0	1735.0203	266.03644	78.570015

Figure 6.12 Execution and results of Query 6-6 for column selection.

Table 6.2 Comparison of selected columns with different cement additions and structural dimensions.

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 Figure 6.13 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 words, the increase of embodied energy and CO_2e caused by higher concrete strength class is offset against a slenderer structural element with 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 $450 \times 450mm^2$ with Column $370 \times 370mm^2$). 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*.

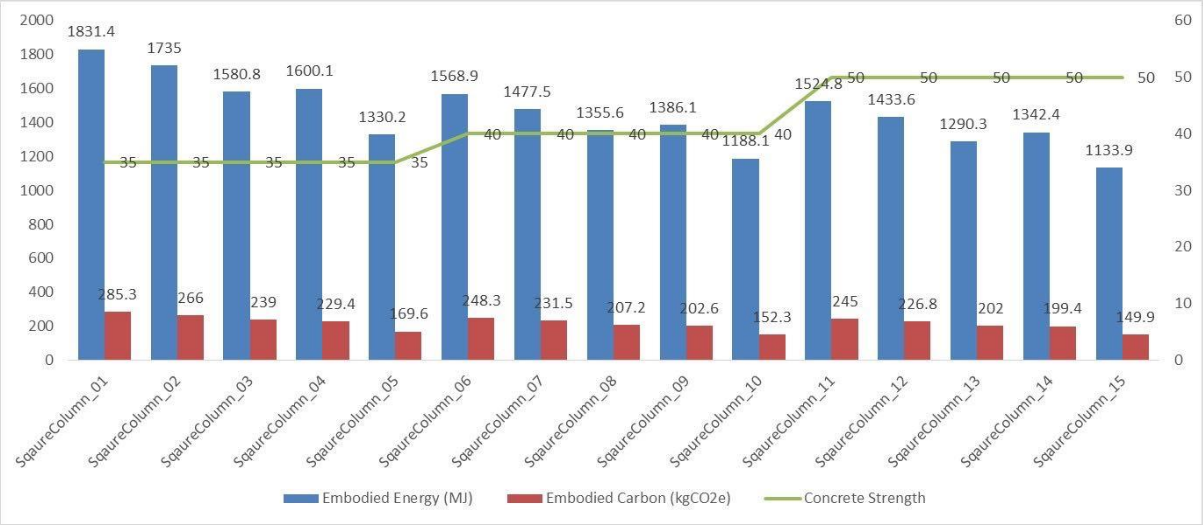


Figure 6.13 Comparison of selected columns with different dimensions and cement additions.

6.3.2.1 Durability

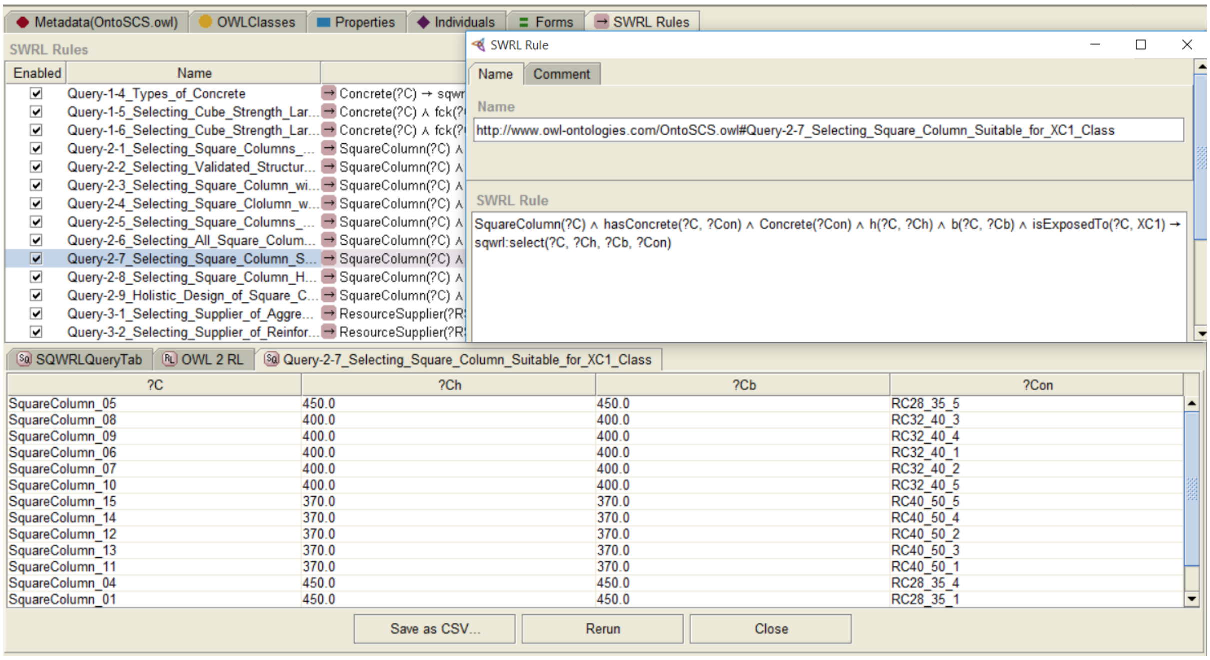
In addition to the structural strength (load capacity) and environmental impact (embodied energy and carbon), there are more factors need to consider when selecting appropriate concrete column. The first one is durability. The durability of concrete structure is influenced by the surrounding environmental conditions. According to BS 8500, different exposure classes are specified to represent various environment conditions that affect the concrete structure. The exposure classification is related to the deterioration processes of carbonation (XC), ingress of chlorides (XD or XS), chemical attack from aggressive ground (ACEC) and freeze-thaw (XF). To meet the requirement of durability, structural engineers should design concrete structure according to the exposure class that may occur to the building. There are two main factors that determine if the concrete structure is suitable for a given exposure class, concrete strength and cover. The BS 8500 gives the recommendation for concrete strength and nominal cover to meet various exposure conditions assumed. Taking the exposure class XC1 as an example, it represents the exposure condition such as internal elements or permanently wet elements. For a structure designed for 50-year working life in this exposure class, the recommendation for concrete strength class and nominal cover should be *C20/25* and *15mm*. In other words, this recommendation can be expressed as a condition (if-then) rule:

***If** strength class equals or greater than C20/50 **and** nominal cover equals or greater than 15mm*
***Then** concrete structure is suitable for XC1 exposure class*

Therefore, in order to consider the exposure class in structural design of this case study, this if-then rule is converted to SWRL rule and added into the OntoSCS ontology. As illustrated in Rule 6-10, the concrete column instances that have *C20/25* or greater strength class as well as *15mm* or thicker cover are defined as suitable for XC1 exposure class. After execution of Rule 6-10, the next step is to select all the suitable concrete columns. Query 6-7 is formulated for this purpose. The output of executing Query 6-7 in SQWRLQueryTab is presented in Figure 6.14, where columns that meet the exposure condition are selected.

Rule 6-10 Defining suitable column for exposure class XC1
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ swrlb:greaterThanOrEqual(?Confck, 25) *∧ Cover(?C, ?CC) ∧ swrlb:greaterThanOrEqual(?CC, 15)* *→ isExposedTo(?C, XC1)*

Query 6-7 Selecting square column suitable for XC1 class
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ isExposedTo(?C, XC1) *→ sqwrl:select(?C, ?Ch, ?Cb, ?Con)*



SWRL Rules

Enabled	Name	
☑	Query-1-4_Types_of_Concrete	Concrete(?C) → sqwr
☑	Query-1-5_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?
☑	Query-1-6_Selecting_Cube_Strength_Lar...	Concrete(?C) ∧ fck(?
☑	Query-2-1_Selecting_Square_Columns_...	SquareColumn(?C) ∧
☑	Query-2-2_Selecting_Validated_Structur...	SquareColumn(?C) ∧
☑	Query-2-3_Selecting_Square_Column_wi...	SquareColumn(?C) ∧
☑	Query-2-4_Selecting_Square_Clolumn_w...	SquareColumn(?C) ∧
☑	Query-2-5_Selecting_Square_Columns_...	SquareColumn(?C) ∧
☑	Query-2-6_Selecting_All_Square_Colum...	SquareColumn(?C) ∧
☑	Query-2-7_Selecting_Square_Column_S...	SquareColumn(?C) ∧
☑	Query-2-8_Selecting_Square_Column_H...	SquareColumn(?C) ∧
☑	Query-2-9_Holistic_Design_of_Square_C...	SquareColumn(?C) ∧
☑	Query-3-1_Selecting_Supplier_of_Aggre...	ResourceSupplier(?R
☑	Query-3-2_Selecting_Supplier_of_Reinfor...	ResourceSupplier(?R

Name

http://www.owl-ontologies.com/OntoSCS.owl#Query-2-7_Selecting_Square_Column_Suitable_for_XC1_Class

SWRL Rule

```
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ isExposedTo(?C, XC1) →
sqwrl:select(?C, ?Ch, ?Cb, ?Con)
```

?C	?Ch	?Cb	?Con
SquareColumn_05	450.0	450.0	RC28_35_5
SquareColumn_08	400.0	400.0	RC32_40_3
SquareColumn_09	400.0	400.0	RC32_40_4
SquareColumn_06	400.0	400.0	RC32_40_1
SquareColumn_07	400.0	400.0	RC32_40_2
SquareColumn_10	400.0	400.0	RC32_40_5
SquareColumn_15	370.0	370.0	RC40_50_5
SquareColumn_14	370.0	370.0	RC40_50_4
SquareColumn_12	370.0	370.0	RC40_50_2
SquareColumn_13	370.0	370.0	RC40_50_3
SquareColumn_11	370.0	370.0	RC40_50_1
SquareColumn_04	450.0	450.0	RC28_35_4
SquareColumn_01	450.0	450.0	RC28_35_1

Figure 6.14 Execution and results of Query 6-7 for column selection.

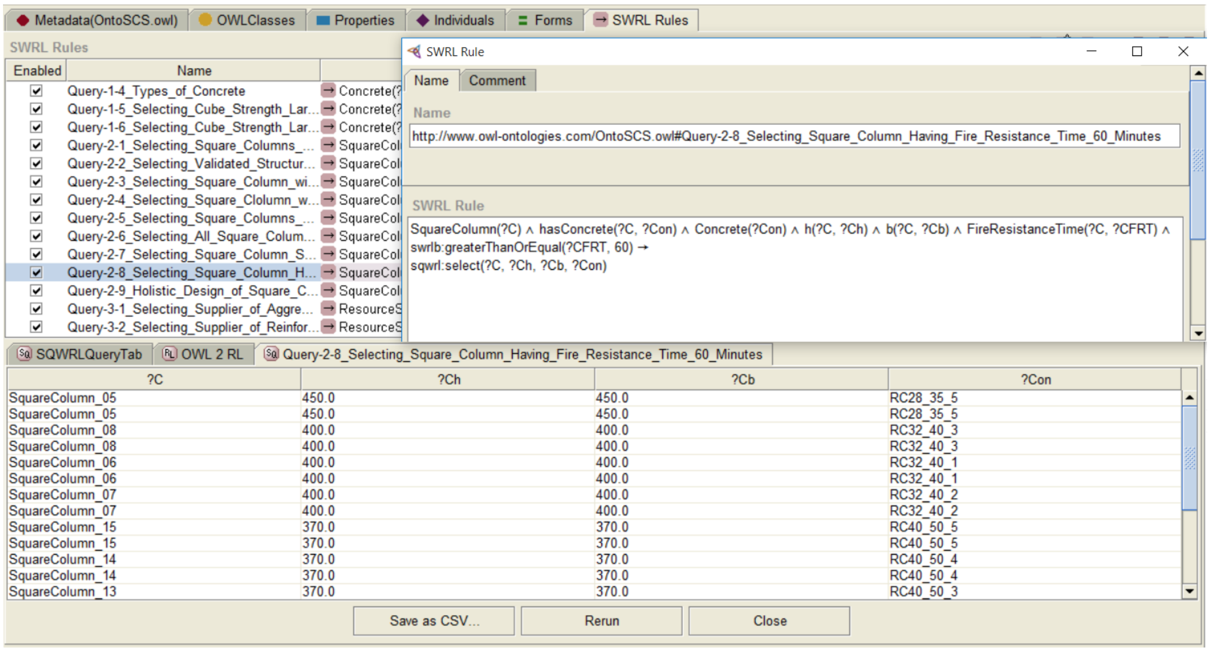
6.3.2.2 Fire resistance

The fire resistance is another factor to consider. When designing a concrete structure, the size of structural members should be governed by the requirements of fire resistance. The BS 8110 (British Standards Institution, 1997) provides the requirements of fire resistance for different structural members, such as Beam, floor and column. The nominal cover and minimum member size determines the fire resistance ability. In general, the increase of size and cover thickness would improve the fire resistance performance. Taking the concrete column as an example, 1 hour of fire resistance requires *200mm* of minimum column size and *25mm* nominal cover, while 1.5 hour requires *300mm* and *25mm* respectively.

In this application, the requirements for fire resistance are embedded through defining corresponding SWRL rules. The Rule 6-11 uses built-in *swirl:greaterThanOrEqual* to justify if a column instance meets the 1 hour fire resistance requirement. Columns that are suited for this requirement could be selected by executing the Query 6-8, as shown in Figure 6.15.

Rule 6-11 Defining fire resistance time 60 minutes for square column
SquareColumn(?C) ∧ b(?C, ?Cb) ∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?Cb, 200) ∧ swrlb:greaterThanOrEqual(?CCo, 25) → FireResistanceTime(?C, 60)

Query 6-8 Selecting square column having fire resistance time 60 minutes
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ FireResistanceTime(?C, ?CFRT) ∧ swrlb:greaterThanOrEqual(?CFRT, 60) → sqwrl:select(?C, ?Ch, ?Cb, ?Con)



Enabled	Name	
☑	Query-1-4_Types_of_Concrete	→ Concrete(?
☑	Query-1-5_Selecting_Cube_Strength_Lar...	→ Concrete(?
☑	Query-1-6_Selecting_Cube_Strength_Lar...	→ Concrete(?
☑	Query-2-1_Selecting_Square_Columns_...	→ SquareCol
☑	Query-2-2_Selecting_Validated_Structur...	→ SquareCol
☑	Query-2-3_Selecting_Square_Column_wi...	→ SquareCol
☑	Query-2-4_Selecting_Square_Clolumn_w...	→ SquareCol
☑	Query-2-5_Selecting_Square_Columns_...	→ SquareCol
☑	Query-2-6_Selecting_All_Square_Colum...	→ SquareCol
☑	Query-2-7_Selecting_Square_Column_S...	→ SquareCol
☑	Query-2-8_Selecting_Square_Column_H...	→ SquareCol
☑	Query-2-9_Holistic_Design_of_Square_C...	→ SquareCol
☑	Query-3-1_Selecting_Supplier_of_Aggre...	→ ResourceS
☑	Query-3-2_Selecting_Supplier_of_Reinfor...	→ ResourceS

Name: http://www.owl-ontologies.com/OntoSCS.owl#Query-2-8_Selecting_Square_Column_Having_Fire_Resistance_Time_60_Minutes

SWRL Rule:

```
SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ FireResistanceTime(?C, ?CFRT) ∧
swrlb:greaterThanOrEqual(?CFRT, 60) →
sqwrl:select(?C, ?Ch, ?Cb, ?Con)
```

Query-2-8_Selecting_Square_Column_Having_Fire_Resistance_Time_60_Minutes

?C	?Ch	?Cb	?Con
SquareColumn_05	450.0	450.0	RC28_35_5
SquareColumn_05	450.0	450.0	RC28_35_5
SquareColumn_08	400.0	400.0	RC32_40_3
SquareColumn_08	400.0	400.0	RC32_40_3
SquareColumn_06	400.0	400.0	RC32_40_1
SquareColumn_06	400.0	400.0	RC32_40_1
SquareColumn_07	400.0	400.0	RC32_40_2
SquareColumn_07	400.0	400.0	RC32_40_2
SquareColumn_15	370.0	370.0	RC40_50_5
SquareColumn_15	370.0	370.0	RC40_50_5
SquareColumn_14	370.0	370.0	RC40_50_4
SquareColumn_14	370.0	370.0	RC40_50_4
SquareColumn_13	370.0	370.0	RC40_50_3

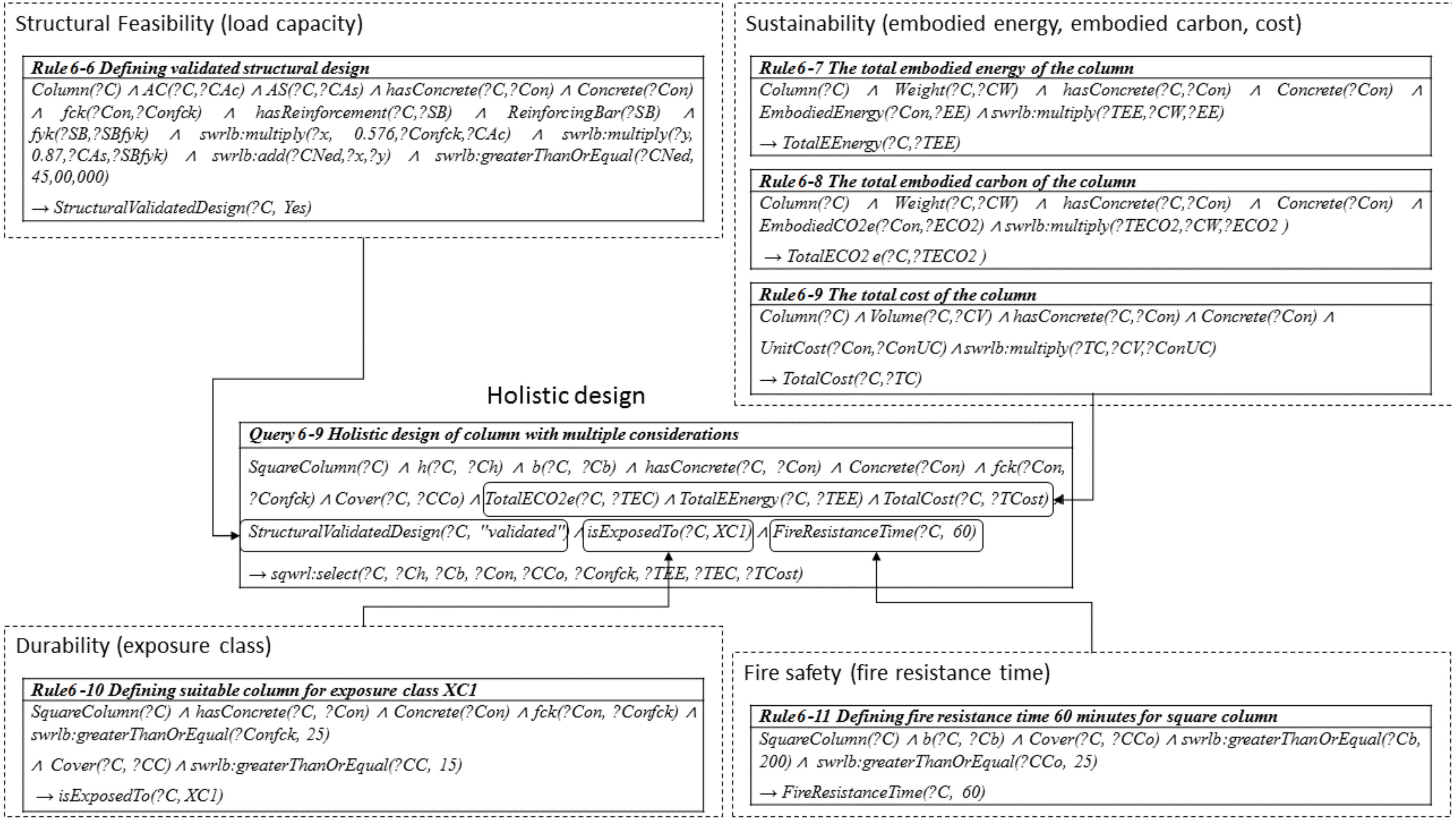
Figure 6.15 Execution and results of Query 6-8 for column selection.

The previous applications have focus on different aspects of structural design, for instance, load capacity, embodied energy and carbon, durability, and fire resistance. Other than the consideration of single aspect, the OntoSCS system is also able to combine all above aspects into a multi-criteria design to achieve a holistic design approach. This is examined in ensuing section.

6.3.3 Application 3 Holistic design with multiple criteria and objectives

From structural engineers' perspective, the holistic design aims to provide optimised structures with full consideration of all the relevant factors that may affect the overall performance. The decision making in holistic design are based on multiple criteria rather than single requirement. These criteria are often interdependent, for example, size of structural member not only affect the load capacity, but also the sustainability, durability and fire safety. Therefore, an example presented in this application is to demonstrate the advanced capability of OntoSCS to provide a holistic approach for multi-objective and multi-criteria structural component selection during design process. Query 6-9 demonstrates how appropriate concrete columns can be selected based on structural feasibility, sustainability, durability and fire safety. As shown in Figure 6.16, multiple SWRL rules, which have been applied to previous applications to meet different criteria, are all taken into account in this case through the integration as single query. By using AxiomeTab of Protégé-OWL, Figure 6.17 further demonstrates how Query 6-9 is linked with other rules sets in OntoSCS system for holistic design.

Query 6-9 Holistic design of column with multiple considerations
SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ Cover(?C, ?CCo) ∧ TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧ TotalCost(?C, ?TCost) ∧ StructuralValidatedDesign(?C, "validated") ∧ isExposedTo(?C, XC1) ∧ FireResistanceTime(?C, 60) *→ sqwrl:select(?C, ?Ch, ?Cb, ?Con, ?CCo, ?Confck, ?TEE, ?TEC, ?TCost)*



Rule 6-6 Defining validated structural design

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) ∧ swrlb:greaterThanOrEqual(?CNed, 45,00,000)

→ StructuralValidatedDesign(?C, Yes)

Rule 6-7 The total embodied energy of the column

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

→ TotalEEnergy(?C,?TEE)

Rule 6-8 The total embodied carbon of the column

Column(?C) ∧ Weight(?C,?CW) ∧ hasConcrete(?C,?Con) ∧ Concrete(?Con) ∧ EmbodiedCO2e(?Con,?ECO2) ∧ swrlb:multiply(?TECO2,?CW,?ECO2)

→ TotalECO2 e(?C,?TECO2)

Rule 6-9 The total cost of the column

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

UnitCost(?Con,?ConUC) ∧ swrlb:multiply(?TC,?CV,?ConUC)

→ TotalCost(?C,?TC)

Query 6-9 Holistic design of column with multiple considerations

SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ Cover(?C, ?CCo) ∧ TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧ TotalCost(?C, ?TCost) StructuralValidatedDesign(?C, "validated") ∧ isExposedTo(?C, XC1) ∧ FireResistanceTime(?C, 60)

→ sqwrl:select(?C, ?Ch, ?Cb, ?Con, ?CCo, ?Confck, ?TEE, ?TEC, ?TCost)

Rule6-10 Defining suitable column for exposure class XC1

SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ swrlb:greaterThanOrEqual(?Confck, 25)

∧ Cover(?C, ?CC) ∧ swrlb:greaterThanOrEqual(?CC, 15)

→ isExposedTo(?C, XC1)

Rule6-11 Defining fire resistance time 60 minutes for square column

SquareColumn(?C) ∧ b(?C, ?Cb) ∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?Cb, 200) ∧ swrlb:greaterThanOrEqual(?CCo, 25)

→ FireResistanceTime(?C, 60)

Figure 6.16 Holistic design query integrating multiple criteria rules.

The results of executing the Query 6-9 in SQWRLQueryTab is shown in Figure 6.18. The concrete column with minimum embodied energy and carbon or costs least can be regarded as the most sustainable structural design option depending on the project's emphasis on environmental or economic aspect.

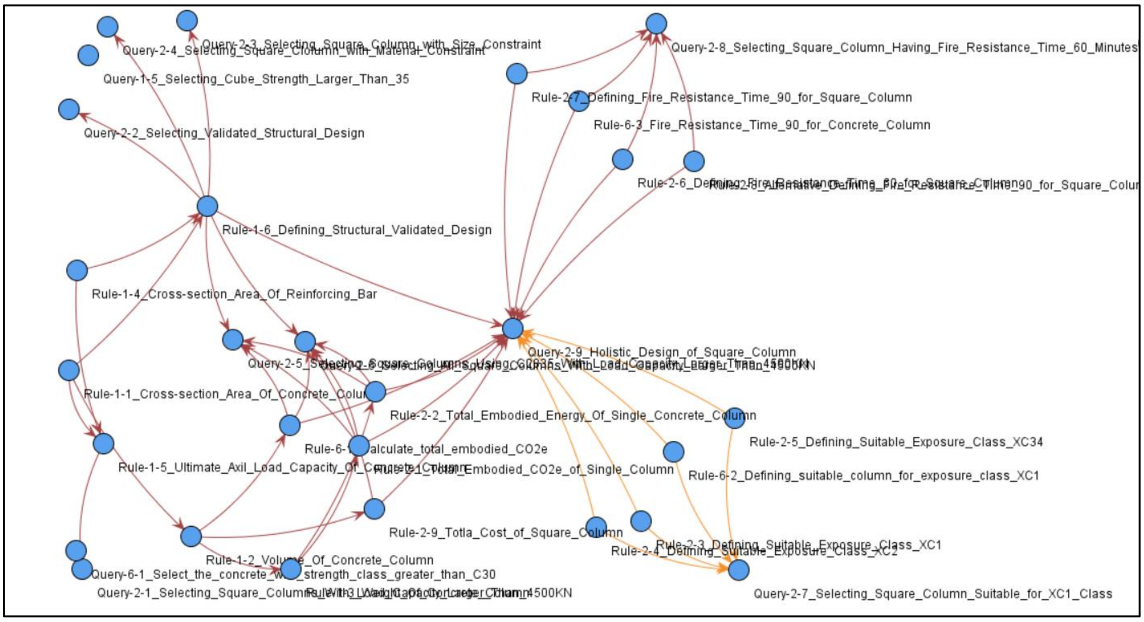
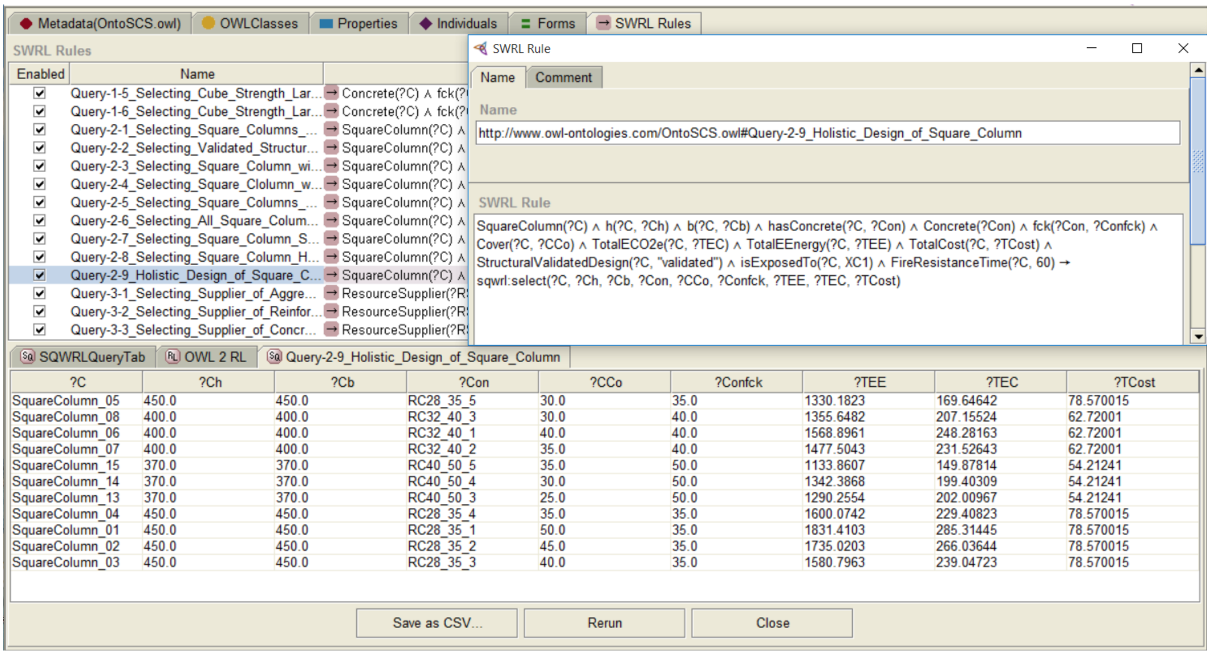


Figure 6.17 Combining SWRL rule set for holistic structural design.



SWRL Rules

Enabled	Name	
☑	Query-1-5_Selecting_Cube_Strength_Lar...	→ Concrete(?C) ∧ fck(?
☑	Query-1-6_Selecting_Cube_Strength_Lar...	→ Concrete(?C) ∧ fck(?
☑	Query-2-1_Selecting_Square_Columns_...	→ SquareColumn(?C) ∧
☑	Query-2-2_Selecting_Validated_Structur...	→ SquareColumn(?C) ∧
☑	Query-2-3_Selecting_Square_Column_wi...	→ SquareColumn(?C) ∧
☑	Query-2-4_Selecting_Square_Clolumn_w...	→ SquareColumn(?C) ∧
☑	Query-2-5_Selecting_Square_Columns_...	→ SquareColumn(?C) ∧
☑	Query-2-6_Selecting_All_Square_Colum...	→ SquareColumn(?C) ∧
☑	Query-2-7_Selecting_Square_Column_S...	→ SquareColumn(?C) ∧
☑	Query-2-8_Selecting_Square_Column_H...	→ SquareColumn(?C) ∧
☑	Query-2-9_Holistic_Design_of_Square_C...	→ SquareColumn(?C) ∧
☑	Query-3-1_Selecting_Supplier_of_Aggre...	→ ResourceSupplier(?R
☑	Query-3-2_Selecting_Supplier_of_Reinfor...	→ ResourceSupplier(?R
☑	Query-3-3_Selecting_Supplier_of_Concr...	→ ResourceSupplier(?R

Name

http://www.owl-ontologies.com/OntoSCS.owl#Query-2-9_Holistic_Design_of_Square_Column

SWRL Rule

```
SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧
Cover(?C, ?CCo) ∧ TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧ TotalCost(?C, ?TCost) ∧
StructuralValidatedDesign(?C, "validated") ∧ isExposedTo(?C, XC1) ∧ FireResistanceTime(?C, 60) →
sqwrl:select(?C, ?Ch, ?Cb, ?Con, ?CCo, ?Confck, ?TEE, ?TEC, ?TCost)
```

?C	?Ch	?Cb	?Con	?CCo	?Confck	?TEE	?TEC	?TCost
SquareColumn_05	450.0	450.0	RC28_35_5	30.0	35.0	1330.1823	169.64642	78.570015
SquareColumn_08	400.0	400.0	RC32_40_3	30.0	40.0	1355.6482	207.15524	62.72001
SquareColumn_06	400.0	400.0	RC32_40_1	40.0	40.0	1568.8961	248.28163	62.72001
SquareColumn_07	400.0	400.0	RC32_40_2	35.0	40.0	1477.5043	231.52643	62.72001
SquareColumn_15	370.0	370.0	RC40_50_5	35.0	50.0	1133.8607	149.87814	54.21241
SquareColumn_14	370.0	370.0	RC40_50_4	30.0	50.0	1342.3868	199.40309	54.21241
SquareColumn_13	370.0	370.0	RC40_50_3	25.0	50.0	1290.2554	202.00967	54.21241
SquareColumn_04	450.0	450.0	RC28_35_4	35.0	35.0	1600.0742	229.40823	78.570015
SquareColumn_01	450.0	450.0	RC28_35_1	50.0	35.0	1831.4103	285.31445	78.570015
SquareColumn_02	450.0	450.0	RC28_35_2	45.0	35.0	1735.0203	266.03644	78.570015
SquareColumn_03	450.0	450.0	RC28_35_3	40.0	35.0	1580.7963	239.04723	78.570015

Figure 6.18 Execution and results of Query 6-9 for column selection.

Figure 6.19 shows how the OntoSCS system provides concrete column design solutions with increasing criteria. Five design alternatives that meets all the design requirements are eventually retrieved from the system.

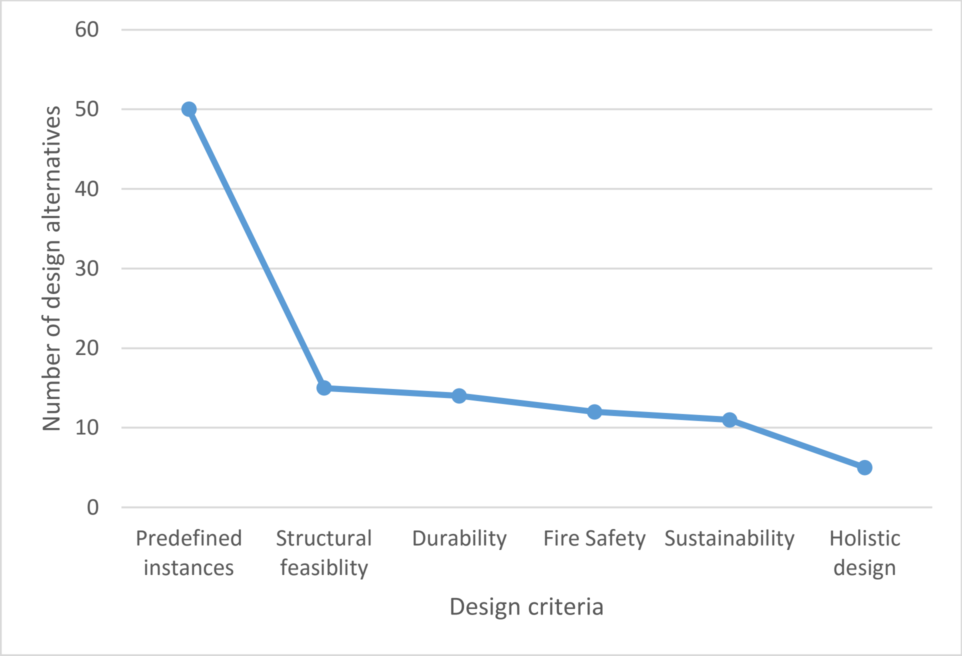


Figure 6.19 Retrieved design alternatives in different design criteria.

6.3.4 Application 4 Structural materials supplier consideration

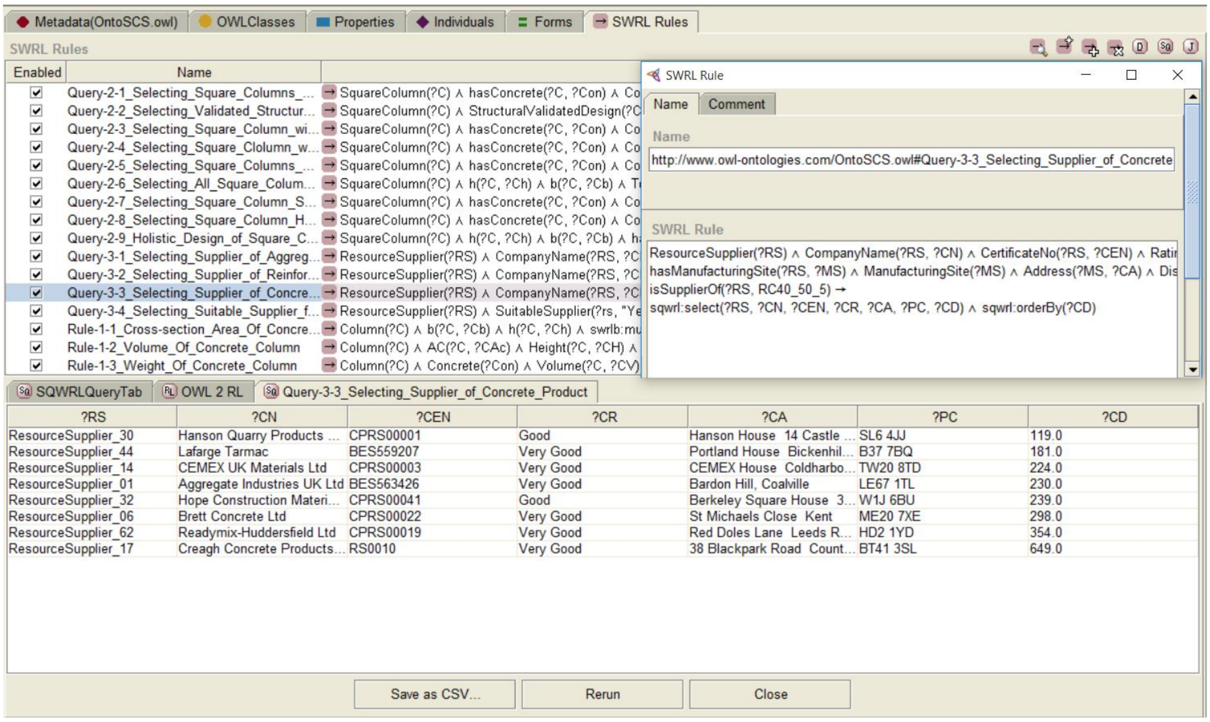
In addition to the selection of material or structural form containing less embodied energy and carbon demonstrated in previous applications, the selection of material supplier also significantly affects sustainability of building. In this application, OntoSCS is used to find a certificated responsible sourcing of construction products from BES 6001 - Framework Standard for the Responsible Sourcing of Construction Products. The significance of this application lies on the extended consideration for supply chain - which demonstrates a new generation BIM oriented full life cycle decision making approach.

Query 6-10 explores the semantic relationships between the construction materials, 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 6-10 is presented in Figure 6.20, where eight 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 from BES 6001, in order to minimise the embodied energy and carbon consumption caused by transport or production.

Query 6-10 Selecting all the suppliers that provide C40/50 concrete product

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)



Enabled	Name	
☑	Query-2-1_Selecting_Square_Columns_...	→ SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Co
☑	Query-2-2_Selecting_Validated_Structur...	→ SquareColumn(?C) ∧ StructuralValidatedDesign(?C
☑	Query-2-3_Selecting_Square_Column_wi...	→ SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Co
☑	Query-2-4_Selecting_Square_Clolumn_w...	→ SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Co
☑	Query-2-5_Selecting_Square_Columns_...	→ SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Co
☑	Query-2-6_Selecting_All_Square_Colum...	→ SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ T
☑	Query-2-7_Selecting_Square_Column_S...	→ SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Co
☑	Query-2-8_Selecting_Square_Column_H...	→ SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Co
☑	Query-2-9_Holistic_Design_of_Square_C...	→ SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ h
☑	Query-3-1_Selecting_Supplier_of_Aggreg...	→ ResourceSupplier(?RS) ∧ CompanyName(?RS, ?C
☑	Query-3-2_Selecting_Supplier_of_Reinfor...	→ ResourceSupplier(?RS) ∧ CompanyName(?RS, ?C
☑	Query-3-3_Selecting_Supplier_of_Concre...	→ ResourceSupplier(?RS) ∧ CompanyName(?RS, ?C
☑	Query-3-4_Selecting_Suitable_Supplier_f...	→ ResourceSupplier(?RS) ∧ SuitableSupplier(?rs, "Ye
☑	Rule-1-1_Cross-section_Area_Of_Concre...	→ Column(?C) ∧ b(?C, ?Cb) ∧ h(?C, ?Ch) ∧ swrlb:mu
☑	Rule-1-2_Volume_Of_Concrete_Column	→ Column(?C) ∧ AC(?C, ?CAc) ∧ Height(?C, ?CH) ∧
☑	Rule-1-3_Weight_Of_Concrete_Column	→ Column(?C) ∧ Concrete(?Con) ∧ Volume(?C, ?CV)

Name

http://www.owl-ontologies.com/OntoSCS.owl#Query-3-3_Selecting_Supplier_of_Concrete

SWRL Rule

```
ResourceSupplier(?RS) ∧ CompanyName(?RS, ?CN) ∧ CertificateNo(?RS, ?CEN) ∧ Ratir
hasManufacturingSite(?RS, ?MS) ∧ ManufacturingSite(?MS) ∧ Address(?MS, ?CA) ∧ Dis
isSupplierOf(?RS, RC40_50_5) →
sqwrl:select(?RS, ?CN, ?CEN, ?CR, ?CA, ?PC, ?CD) ∧ sqwrl:orderBy(?CD)
```

?RS	?CN	?CEN	?CR	?CA	?PC	?CD
ResourceSupplier_30	Hanson Quarry Products ...	CPRS00001	Good	Hanson House 14 Castle ...	SL6 4JJ	119.0
ResourceSupplier_44	Lafarge Tarmac	BES559207	Very Good	Portland House Bickenhil...	B37 7BQ	181.0
ResourceSupplier_14	CEMEX UK Materials Ltd	CPRS00003	Very Good	CEMEX House Coldharbo...	TW20 8TD	224.0
ResourceSupplier_01	Aggregate Industries UK Ltd	BES563426	Very Good	Bardon Hill, Coalville	LE67 1TL	230.0
ResourceSupplier_32	Hope Construction Materi...	CPRS00041	Good	Berkeley Square House 3...	W1J 6BU	239.0
ResourceSupplier_06	Brett Concrete Ltd	CPRS00022	Very Good	St Michaels Close Kent	ME20 7XE	298.0
ResourceSupplier_62	Readymix-Huddersfield Ltd	CPRS00019	Very Good	Red Doles Lane Leeds R...	HD2 1YD	354.0
ResourceSupplier_17	Creagh Concrete Products...	RS0010	Very Good	38 Blackpark Road Count...	BT41 3SL	649.0

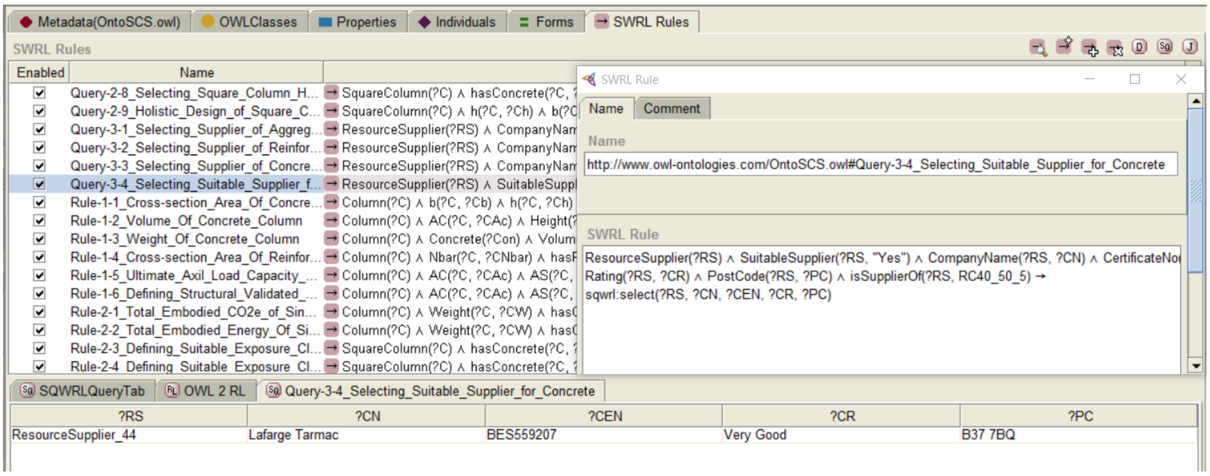
Figure 6.20 Execution and results of Query 6-10 for supplier selection.

In practice, the end-user needs to determine the most suitable supplier for this project based on the query results from above example. The selection query in above example is not applicable enough for this purpose. It requires defining criteria to be fulfilled by suitable supplier. In this case, the product rating and the distance between supplier to construction site are chosen as the criteria since they are directly associated with the sustainability of structural materials. It is noteworthy that the criteria could altered depending on the requirements from end-users. Therefore, the suitable supplier is the one with highest product rating and shortest distance. To capture the criteria, *swrlb:lessThan* and data-type property *"Rating"* and *"Distance"* are combines in Rule 6-12. By executing Rule 6-12, new string value *"Yes"* will be populated into the *"SuitableSupplier"* data-type property of *"ResourceSupplier"* instances that meet the criteria. Therefore, the information about the suitable supplier such as company name, certificate number and postcode could be retrieved using Query 6-11.

Rule 6-12 Defining suitable supplier for C40/50 concrete product
ResourceSupplier(?RS) ∧ Rating(?RS, "Very Good") ∧ hasManufacturingSite(?RS, ?MS) ∧ ManufacturingSite(?MS) ∧ Distance(?MS, ?CD) ∧ swrlb:lessThan(?CD, 200) *→ SuitableSupplier(?RS, "Yes")*

Query 6-11 Selecting the suitable supplier that provides C40/50 concrete product
ResourceSupplier(?RS) ∧ SuitableSupplier(?RS, "Yes") ∧ CompanyName(?RS, ?CN) ∧ CertificateNo(?RS, ?CEN) ∧ Rating(?RS, ?CR) ∧ PostCode(?RS, ?PC) ∧ isSupplierOf(?RS, RC40_50_5) *→ sqwrl:select(?RS, ?CN, ?CEN, ?CR, ?PC)*

The output of Query 6-11 is shown in Figure 6.21, where the suitable supplier is selected for the *C40/50* concrete material.



Enabled	Name	
☑	Query-2-8_Selecting_Square_Column_H...	SquareColumn(?C) ∧ hasConcrete(?C,
☑	Query-2-9_Holistic_Design_of_Square_C...	SquareColumn(?C) ∧ h(?C, ?Ch) ∧ b(?C
☑	Query-3-1_Selecting_Supplier_of_Aggreg...	ResourceSupplier(?RS) ∧ CompanyNam
☑	Query-3-2_Selecting_Supplier_of_Reinfor...	ResourceSupplier(?RS) ∧ CompanyNam
☑	Query-3-3_Selecting_Supplier_of_Concre...	ResourceSupplier(?RS) ∧ CompanyNam
☑	Query-3-4_Selecting_Suitable_Supplier_f...	ResourceSupplier(?RS) ∧ SuitableSuppl
☑	Rule-1-1_Cross-section_Area_Of_Concre...	Column(?C) ∧ b(?C, ?Cb) ∧ h(?C, ?Ch)
☑	Rule-1-2_Volume_Of_Concrete_Column	Column(?C) ∧ AC(?C, ?CAc) ∧ Height(?
☑	Rule-1-3_Weight_Of_Concrete_Column	Column(?C) ∧ Concrete(?Con) ∧ Volum
☑	Rule-1-4_Cross-section_Area_Of_Reinfor...	Column(?C) ∧ Nbar(?C, ?CNbar) ∧ hasR
☑	Rule-1-5_Ultimate_Axil_Load_Capacity_...	Column(?C) ∧ AC(?C, ?CAc) ∧ AS(?C,
☑	Rule-1-6_Defining_Structural_Validated_...	Column(?C) ∧ AC(?C, ?CAc) ∧ AS(?C,
☑	Rule-2-1_Total_Embodied_CO2e_of_Sin...	Column(?C) ∧ Weight(?C, ?CW) ∧ has(
☑	Rule-2-2_Total_Embodied_Energy_Of_Si...	Column(?C) ∧ Weight(?C, ?CW) ∧ has(
☑	Rule-2-3_Defining_Suitable_Exposure_Cl...	SquareColumn(?C) ∧ hasConcrete(?C,
☑	Rule-2-4_Defining_Suitable_Exposure_Cl...	SquareColumn(?C) ∧ hasConcrete(?C,

Name: http://www.owl-ontologies.com/OntoSCS.owl#Query-3-4_Selecting_Suitable_Supplier_for_Concrete

SWRL Rule:

```
ResourceSupplier(?RS) ∧ SuitableSupplier(?RS, "Yes") ∧ CompanyName(?RS, ?CN) ∧ CertificateNo(
Rating(?RS, ?CR) ∧ PostCode(?RS, ?PC) ∧ isSupplierOf(?RS, RC40_50_5) →
sqwrl:select(?RS, ?CN, ?CEN, ?CR, ?PC)
```

?RS	?CN	?CEN	?CR	?PC
ResourceSupplier_44	Lafarge Tarmac	BES559207	Very Good	B37 7BQ

Figure 6.21 Execution and results of Query 6-11 for supplier selection.

6.3.5 Application 5 Sustainability assessment of structural member

In order to extend the applicability of OntoSCS system, current sustainability rating system can be taken into account and assessment criteria that is associated with structural design can be incorporated into this system. In the UK, BREEAM is the most common rating system employed for assessing the sustainable credentials of a building project. It evaluates the sustainable performance of buildings across the following areas: management, energy use, health and well-being, pollution, transport, land use, ecology, materials, and water. Among these assessment areas, materials are most directly related to building structures. In the material section of BRREAM technical manual, responsibly sourced material is encouraged for key building element. Structural engineers can gain maximum credits throughout selecting material from responsible sourcing accredited under BES 6001 which has been demonstrated in last application.

The assessment criterion is established on a tier level and points awarded system, as illustrated in Table 6.3. The tier level of building material is determined by the product rating in BES 6001 scheme, and corresponding points are accredited accordingly. For example, a structural frame that employs concrete product with *"Excellent"* product rating could achieve tier level 2 and 3.5 points.

Table 6.3 Responsible sourcing tier level and points in BREEAM.

BES 6001 Product certification	***Tier level***	***Points***
	1	4.0
Excellent	2	3.5
Very good	3	3.0
Good	4	2.5
Pass	5	2.0
	6	1.5
	7	1.0
	8	0

To incorporate this criterion into OntoSCS system, this tier/point system need to be converted to a set of condition rules and then expressed using SWRL. The previous example *"a concrete product with 'Excellent' product rating could achieve tier level 2 and 3.5 points"* can be translated as following rule:

If *Column employs concrete product*
and *concrete product is rated as "Excellent"*
Then *Column achieve tier level 2 And 3.5 points*

Therefore, the SWRL rule can be developed as Rule 6-13, and rules for other tier level can be developed in the same manner.

Rule 6-13 Responsible sourcing tier level and points for Excellent product

SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ isSuppliedBy(?Con, ?RS) ∧ ResourceSupplier(?RS) ∧ Rating(?RS, Excellent)

→ TierLevel(?C, 2) ∧ Points(?C, 3.5)

6.4 Summary

In this chapter, a real-world design case study is implemented to test the prototype system. The Semantic Web technologies including SWRL rules and SQWRL queries are employed to conduct reasoning and retrieval task. The effectiveness of OntoSCS system is demonstrated by executing the rules and queries in different design scenarios. The rules are used to calculate the properties of structural element and load capacity in typical structural design application. Moreover, in sustainable structural design application, they have been used to evaluate the amount of embodied energy and carbon as well as the cost associated with structural member. This leads to the achievement of sustainable structural design. Additionally, two more factors, durability and fire resistance are taken into account to the structural design application. Based on the outcome from previous applications, a holistic approach involving multiple design criteria is established using SQWRL query to determine the most sustainable design option with considerations of structural feasibility, durability, fire safety, cost, environmental impact. Additionally, the use of queries expedites the decision-making process when selecting the suitable structural material supplier. Lastly, the BRREAM assessment criteria are modelled as SWRL rule set in the system, which allows structural engineers to understand how many sustainable credentials can be achieved from the selection of material product.

Apart from examples demonstrated in this chapter, further rules and queries can be added to enrich the ontology depending on the purposes. Although only single case study with applications is presented, the flexibility and extensibility of the OntoSCS ontology ensures that it is possible to employ more case studies for other types of structural materials or structural forms, such as steel and timber structure.

Chapter 7 Conclusion

The motivation of this research is established on the increasing awareness of improving sustainability and mitigating the environmental impact from building construction sector, including structural design. One of the effective approach to improve the sustainability is through more efficient knowledge management about sustainable design during structural design stage. The current web technology is limited for this purpose due to the lack of semantic and inefficient searching. The Semantic Web technology has been proposed to overcome these limitations, which provides great opportunities for construction sector to manage domain knowledge in a more organised and efficient way. Therefore, the research question has been asked:

How Semantic Web techniques can be used to model structural design and sustainability related knowledge to support the structural engineer's decisions at an early stage?

To answer this research question, the following research objectives have been formulated:

- Identify domain knowledge and methodology for sustainable structural design;
- Identify the gaps in current practice in managing sustainable building structure knowledge;

- Explore the Semantic Web technologies and how to use the technologies to bridge the gaps;
- Establish a holistic knowledge model capturing sustainable structural design information and knowledge using Semantic Web technologies;
- Implement a sustainable design decision-support prototype system based on knowledge model;
- Validate the prototype system using typical structural design case to demonstrate the applicability of the system.

7.1 Attainment of the research objectives

1. Identify domain knowledge and methodology of sustainable structural design

A literature review is undertaken in Chapter 2 to achieve the first objective. The review includes an overview of the broad nature of sustainability, sustainable development in construction sector, and methods in structural engineering to improve sustainability. The overview facilitates the understanding of the sustainable building technologies and methods applied in structural design area with focus on concrete structure. Important indicators for measuring sustainability in building structures such as embodied energy and carbon are examined. With regards to the knowledge management, one of the key findings is that the resources of and guidance to sustainable structural design are distributed in various locations and represented in different formats. On the basis of literature review, the challenges remaining in the sustainable structural design are analysed to achieve the second objective.

2. ***Identify the gaps in current practice in managing sustainable building structure knowledge***

After reviewing the current state of sustainable structural design, information related challenges are identified. Firstly, it is considered deficient for knowledge management in AEC industry due to the complex and fragmented nature of building construction. Particularly, the information and knowledge related to sustainable building is abundant and fragmented, which is distributed in various locations using different formats. It is challenging and time consuming for structural engineers to find and verify the information in design stage. Secondly, the information about sustainable building does not only serve structural engineers but other professions across building construction sectors. The synonym of terms used in sustainable design often causes confusion. Furthermore, the structural engineers are limited to make informed decision with consideration of sustainability due to the lack of tools on quantitatively evaluating the sustainability of design solutions at early stages. Existing sustainability tools focus heavily on complete buildings rather than design phase. Finally, current practice of structural design only generates very few design solution, lacking the ability of suggesting alternative design solutions with potential sustainable benefits.

3. ***Explore the Semantic Web technology and how to use it to bridge the gaps***

Information retrieval in current web relies heavily on human's interpretation, because of a lack of semantics in both search engines and HTML based web pages. The Semantic Web is proposed to enable data on the web to be processed by both human and machine, therefore improving the efficiency of information retrieval and sharing. In Chapter 2, the concepts and core technologies of Semantic Web are explored. Key Semantic Web technologies such as ontology and semantic rules are identified for the use of modelling domain knowledge in this study. Firstly, OWL ontology provides a unified format and platform to structurally manage knowledge and information in structural design as well as sustainability domain. The semantics offered by ontology eliminate the ambiguity in the information. In addition to the structured knowledge represented by ontology, SWRL rule can be used to model logic design principles and constraint knowledge in structural design code and sustainability guidance. Its ability of reasoning enables design rules and calculation to be processed by computer, while the query function allows meaningful results can be retrieved. Therefore, OWL ontology combining with SWRL rule is very useful for developing a decision-support tool offering sustainable evaluation of design solution and suggestion of design alternatives with less environmental impact at early design stage.

4. Establish a knowledge model capturing sustainable structural design information and knowledge using Semantic Web technologies

The establishment of knowledge model of sustainable structural design consists of three major tasks: identification of domain knowledge, identification of methodology and identification of language. The first task is completed with the first and second objectives achieved. The main concepts and relationships between concepts are captured and represented in an UML diagram. With regards to the second task, common methodologies of knowledge engineering and ontology development are explored. CommonKADS are selected as the knowledge acquisition method for sustainable structural design domain. Ontology Development 101 methodology is the guide for developing ontology and implementing in software environment. In the third task, the main aim is to select appropriate ontology and rule language to ensure the rich expressiveness and reason ability of the developed ontology. OWL DL and SWRL are the Semantic Web languages used in this study. In summary, the knowledge model for sustainable structural design is established based on criteria elicited from design regulation and process, as well as data collected from database and online resource by using selected languages.

5. *Implement a sustainability design-decision-support prototype system based on knowledge model*

After the fourth objective achieved, the implementation of prototype system in software environment is based on the developed knowledge model. The prototype system architecture is constituted by three parts: knowledge base, ontology management system and inference rule engine. The knowledge base is where the developed ontology and rules are stored, which in this case a single OWL file is used. Protégé-OWL is selected as ontology management system for editing ontology and rules. JESS engine is the rule engine used in this prototype system providing reasoning function. The OntoSCS prototype system implementation consists of two parts: ontology development and rule development. Following the steps suggested in Ontology Development 101 methodology, the OntoSCS ontology is completed in Protégé-OWL and extended to include SWRL rules and SQWRL queries.

6. *Validate the prototype system using typical structural design case to demonstrate the applicability of the system*

A case study of concrete column design is employed to achieve this objective. The OntoSCS prototype system is validated through a group of different design scenario with single or multiple constraints. Firstly, by querying the ontology using SQWRL queries, the system is able to provide structural design solution with single criterion. Secondly, more complicated queries are applied to demonstrate how the system provides multiple structural design alternatives with different amount of embodied energy and carbon. Additionally, a holistic approach for sustainable structural design is achieved by considering more aspects related to building structure. The selection of material supplier is also presented in the case study to demonstrate the sustainable consideration beyond design stage using the system. Finally, the integration of structural design and sustainability assessment system are explored in the last application of case study.

The achievement of all objectives of this study leads to the answer to the research question. During the pursuit of research objectives, key findings are identified and listed as follow.

7.2 Research findings

Findings from review of sustainable structural design

1. The increasing awareness of improving sustainability in construction sector has boosted enormous amount of information published by government, professional institutes, and researchers. However, challenges raised when the professions in construction sector try to take advantage of the information. The structural engineering is an example. Information related to sustainable development are distributed in various paper guidance, databases and web pages. The elicitation process of the knowledge and information is difficult and time consuming for structural engineers. Due to a lack of efficient information and knowledge management tool, engineers often suffer from overwhelming and fragmented sustainability related information.

2. From structural engineers' perspective, there are mainly three ways of reducing embodied energy and carbon. 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. A holistic approach to consider these ways as a whole together with other structural design criteria is generally lacking.

3. Current sustainability assessment tools put emphasis on completed buildings instead of building in design. Moreover, the sustainability of building is always evaluated in the relatively late stage which loses the opportunity to incorporate changes. At the early structural design stage, the structural engineers are limited to make positive impact on sustainability, blaming for the absence of decision-support tool that could quantitatively specify the impact associated with structural element.

4. From literature review, it is emerged that most research on sustainable structural design uses embodied energy or embodied carbon as parameters to evaluate the environmental aspect of sustainability. In addition, cost of structural material is considered to measure the economic aspect of sustainability. Both of these two parameters are adopted as indicators in the ontology developed in this study.

Findings from review of the Semantic Web

1. There are limitations of processing information by current web technologies due to the lack of searching based on the semantics of documents and queries.

2. The review reveals a trend that there is increasing number of research in construction domain adopting Semantic Web technologies in a wide range of applications. The feasibility of these applications have corroborated the shift of knowledge management

in construction industry from human interpretation based approach to automated machine processing based approach.

3. The finding from review also presents that despite the large number of applications, most of ontology developments remain at conceptualisation of domain knowledge and establishment of lightweight ontologies. Majority of applications focus on the construction project and facility management area, with little attention paid on structural design and building sustainability.

4. It is found that current Semantic Web applications in construction area tends to develop individual ontologies without considering reuse available semantic resource to maximising the interoperability between applications. In this study, ifcOWL has been identified as an appropriate semantic resource for developing OntoSCS ontology.

5. The combination of OWL ontology and SWRL rules is very useful for model structural design domain knowledge. The concepts in domain knowledge, attributes of the concepts and their relationships are organised in OWL ontology. Structural design criteria and rules can be represented by SWRL rules to extend the ontology. This double-layer structure, the open-world assumption of ontology with logic rules, enables the flexibility and further extensibility of the system.

7.3 Contribution to knowledge

This study has proposed and realised an innovative ontology based holistic decision support framework, which can be leveraged by structural engineer to design more sustainable structures with systematic consideration for structure feasibility, durability, safety, embodied energy, CO_2 emission, cost, supplier selection, and sustainability assessment.

7.3.1 Theoretical contribution

1. This study identifies the need for a holistic approach that integrate structural design knowledge and sustainable development information.
2. This study systematically reviews the applications of the Semantic Web, especially ontology in construction sector, which establishes an understanding of broader context of this study.
3. This study establishes a Semantic Web approach to represent both concepts in structural design regulation and associated sustainability information through OWL ontology modelling.
4. This study demonstrates an approach that uses SWRL rules to represent structural design criteria and uses reasoning function to conduct structural design calculation, which illustrates the possibility of shift from paper based design regulation to Semantic Web based e-regulation.

7.3.2 Practical contribution

1. This study has developed an ontology to integrate structural design domain and sustainability domain by modelling the shared concepts and inter-connected relationships.
2. This study develops a Semantic Web based decision-support application to enhance current concrete structural design process by providing multiple design alternatives with different sustainable performance.

3. This study exploits SWRL rules and SQWRL queries in the prototype system for multi-criteria selection of structural components to realise holistic consideration in sustainable structural design.

4. The documentation of this study through publications provides a semantic resource in construction sector available for future reuse. The core concept presented in this thesis has been published in Energy and Buildings journal.

7.4 Limitations of the research

The major limitation of this study lies in fact that the Semantic Web technologies are still under development. The full potential of Sematic Web is difficult to be fulfilled due to the inadequate constitute technology. The capability of SWRL rule is an illustration of this limitation. SWRL rules were built to infer new property relationships between existing individuals. However, SWRL shares OWL’s open world assumption, which restricts some reasoning abilities. In the open world assumption, something cannot be determined to not exist until explicitly stated (Tessier and Wang, 2013). Additionally, the mathematical built-ins of SWRL only offers a small set of basic computational operations. Complex mathematical formulas could not be directly converted into SWRL rule format. For example, it is challenging to express equations for stability of structural column using SWRL rules, which limits the exploitation of Semantic Web technologies in e-regulation development.

Secondly, in the case study of the structural design applications, only structural member such as concrete column is considered. In practice, prior to the component detailing design, choices on different structural forms at conceptual design stage also contribute to the overall sustainability of building. Although the underlying design principles of other structural forms such as masonry structure or steel structure is similar to the concrete structure example demonstrated in this study, the evaluation and comparison of sustainability in whole structure scale is more complicated than structural member scale. Because SWRL is limited in handling complex computational operations, it is difficult to represent design process of entire building structure without using external tools.

Thirdly, the relatively small number of instances in this study, which are manually populated in OntoSCS ontology, is insufficient in some complicated design cases. Additionally, the values of each sustainable indicator for structural material are only collected from single database, for example the embodied energy and carbon from ICE database. To maximise the benefit of using ontology in knowledge management in building construction project, it is more convincing to employ automated information retrieval techniques in ontology development, in order to identify, access and elicit substantial building information from historical data and other databases related to building sustainability. Moreover, connection and communication with other ontologies in construction domain are not discussed in this study.

Finally, the prototype system OntoSCS is limited in the Protégé software environment. Using SWRLTab for defining structural design principles and query knowledge base is still challenging for structural engineers with little knowledge about ontology engineering.

Chapter 8 Future Work

Because of the scope of research and time constraint, a PhD research can only focus on a specific issue in a domain. For instance, this study investigates the use of Semantic Web technology to facilitate sustainable development in structural design domain. However, it is important to explore how this study can be further extended, and how the approach adopted in this work can be implemented for other applications in the research context. Therefore, this section discusses the future work of this research in three perspectives: expand the scope of this study, develop interface for prototype system, and implement the approach for other domains in research context.

8.1 Expand the scale of this study

This study primarily focuses on applying Semantic Web technologies on sustainable design of concrete structure. The scope of this study can be expanded in two dimensions: internal and external.

8.1.1 Internal enrichment of OntoSCS ontology

1. Firstly, because the essential classes defined in the OntoSCS ontology are elicited from ifcOWL, the prototype system developed in this study is flexible to include more

structural materials or structural components. For example, system could be enriched by adding steel structural member using same ontology and rule development approach to import steel structure design knowledge.

2. As discussed in Chapter 7, only structural member such as concrete column is considered in this study. However, the decision of structural forms at conceptual design stage contributes significantly to the overall sustainability of building. Therefore, it is important to consider how to extend the system to whole structure scale. Due to the limitation of SWRL rules in dealing with complex structural analysis, it is possible to apply an alternative approach of using historical data of whole building project rather than calculate individual structural elements. For example, using automated information retrieval techniques in ontology development process is able to integrate building information of previous projects into the ontology. SWRL rules is useful in this approach for comparing the characteristic of design with existing building projects, and then selecting similar design solutions with maximum sustainability.

3. Thirdly, 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. Additional indicators related to sustainability such as ecological footprint and lifecycle cost, can be nonetheless added in to system to represent more comprehensive situation in practice.

4. Finally, the Semantic Web based holistic design approach presented in this case considers structural feasibility, sustainability, durability and fire safety requirements. It is feasible to apply more requirements from other disciplines such as constructability by converting the constraints in construction regulation to SWRL rules, in order to guide structural engineers with more comprehensive considerations.

8.1.2 External integration with other systems

The research by Dibley et al. (2015) introduced in Section 2.2.3.6 provides a good example of integrating an ontology with agent system and sensors. It is possible to apply similar approach for the system proposed in this thesis to create an integrated framework for building design. The OntoSCS Ontology capturing human knowledge into a computer understandable format could act as a knowledge repository. The link between structural design/ analysis software and ontology can be achieved by an appropriate software implementation, such as a multi-agent system. This framework could provide intelligent decision support through reasoning and rea-time queries.

8.2 Develop interface

In this study, a prototype system OntoSCS is developed to answer the research question that structural design could be enhanced with sustainability information using Semantic Web technologies. To prove a novel concept, the development of this prototype system is conducted in Protégé-OWL software environment. However, it is challenging for end-users with limited or no knowledge about the software and its plug-ins. There is a need for developing a user-friendly interface based on the OWL API for this back-end system to improve its usability. There are two reasonable platforms for the establishment of interface. The first one is BIM platform such as Autodesk Revit. Current construction industry increasingly relies on BIM technology for visualisation and information exchange. Semantic Web based system is able to enhance current BIM system with knowledge modelling, machine reasoning and interoperability. For example, the visualisation of structural design options and their sustainability information provided respectively by BIM system and Semantic Web based knowledge system could facilitate the decision-making process. The second platform is the web. A web-based knowledge system could improve the situation of fragmented information and knowledge management on current web. More importantly, the easy-to-access feature of web platform could potentially provide more opportunities to incorporate this system into different construction projects.

8.3 Adopt the approach to other domains

Moreover, the methodology of developing OntoSCS system is applicable for ontology developments in other research areas of construction 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 could provide a solution integrating all phases of building life cycle and allowing designers to take decisions from a holistic perspective. The advantage of reasoning function of ontology-based knowledge system could facilitate most of the decision making processes in building life cycle. Eventually, as illustrated in Figure 8.1, a building knowledge layer consisting of various domain ontologies sharing key concepts of core building construction ontology could be established on top of building information layer.

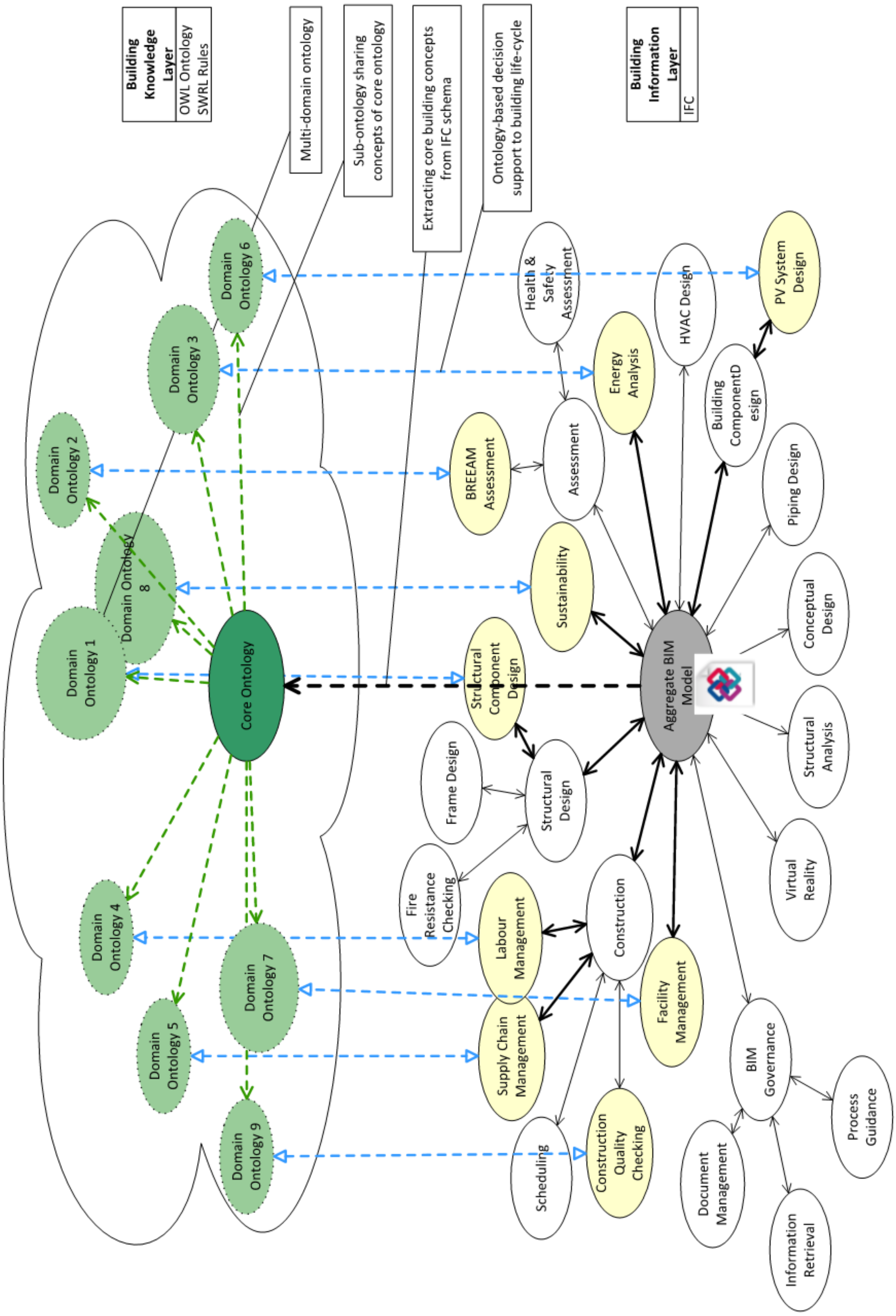


Figure 8.1 Knowledge layer with construction domain ontologies in building lifecycle.

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Appendix 1 Excerpt of OntoSCS OWL ontology

```
<?xml version="1.0"?>
<rdf:RDF
  xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#"
  xmlns:protege="http://protege.stanford.edu/plugins/owl/protege#"
  xmlns:xsp="http://www.owl-ontologies.com/2005/08/07/xsp.owl#"
  xmlns:owl="http://www.w3.org/2002/07/owl#"
  xmlns="http://www.owl-ontologies.com/OntoSCS.owl#"
  xmlns:sqwrl="http://sqwrl.stanford.edu/ontologies/built-ins/3.4/sqwrl.owl#"
  xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
  xmlns:swrl="http://www.w3.org/2003/11/swrl#"
  xmlns:swrlb="http://www.w3.org/2003/11/swrlb#"
  xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
  xmlns:swrla="http://swrl.stanford.edu/ontologies/3.3/swrla.owl#"
 xml:base="http://www.owl-ontologies.com/OntoSCS.owl">
 <owl:Ontology rdf:about="">
  <owl:imports rdf:resource="http://swrl.stanford.edu/ontologies/3.3/swrla.owl"/>
  <owl:imports rdf:resource="http://sqwrl.stanford.edu/ontologies/built-ins/3.4/sqwrl.owl"/>
 </owl:Ontology>
 <owl:Class rdf:ID="BuildingStory">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="SpatialStructureElement"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:about="#SpatialStructureElement">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="SpatialElement"/>
  </rdfs:subClassOf>
 </owl:Class>
 <owl:Class rdf:ID="Concrete">
  <rdfs:subClassOf>
   <owl:Class rdf:ID="Material"/>
  </rdfs:subClassOf>
 </owl:Class>
```

```
<owl:Class rdf:about="#Material">
  <rdfs:subClassOf>
    <owl:Class rdf:ID="MaterialDefinition"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Roof">
  <rdfs:subClassOf>
    <owl:Class rdf:ID="BuildingElement"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="GEN2">
  <rdfs:subClassOf rdf:resource="#Concrete"/>
</owl:Class>
<owl:Class rdf:ID="Slab">
  <rdfs:subClassOf>
    <owl:Class rdf:about="#BuildingElement"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="ConstructionSite">
  <rdfs:subClassOf>
    <owl:Class rdf:ID="Site"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Plate">
  <rdfs:subClassOf>
    <owl:Class rdf:about="#BuildingElement"/>
  </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="RC40_50">
  <rdfs:subClassOf rdf:resource="#Concrete"/>
</owl:Class>
<owl:Class rdf:ID="PAV1">
  <rdfs:subClassOf rdf:resource="#Concrete"/>
</owl:Class>
<owl:Class rdf:ID="RC28_35">
```

```
 <rdfs:subClassOf rdf:resource="#Concrete"/>
</owl:Class>
<owl:Class rdf:about="#Site">
 <rdfs:subClassOf rdf:resource="#SpatialStructureElement"/>
</owl:Class>
<owl:Class rdf:ID="MaterialConstituent">
 <rdfs:subClassOf rdf:resource="#MaterialDefinition"/>
</owl:Class>
<owl:Class rdf:ID="Column">
 <rdfs:subClassOf>
  <owl:Class rdf:about="#BuildingElement"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="RC25_30">
 <rdfs:subClassOf rdf:resource="#Concrete"/>
</owl:Class>
<owl:Class rdf:ID="Pile">
 <rdfs:subClassOf>
  <owl:Class rdf:about="#BuildingElement"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="ElementComponent">
 <rdfs:subClassOf>
  <owl:Class rdf:ID="Element"/>
 </rdfs:subClassOf>
</owl:Class>
<owl:Class rdf:ID="Environment"/>
<owl:Class rdf:ID="GEN1">
 <rdfs:subClassOf rdf:resource="#Concrete"/>
</owl:Class>
<owl:Class rdf:ID="Stair">
 <rdfs:subClassOf>
  <owl:Class rdf:about="#BuildingElement"/>
 </rdfs:subClassOf>
</owl:Class>
```

Appendix 2 SWRL rules and SQWRL queries

SWRL rule set

Rule-1-1_Cross-section_Area_Of_Concrete_Column

Cross-section_Area_Of_Concrete_Column

Column(?C) ∧ b(?C, ?Cb) ∧ h(?C, ?Ch) ∧ swrlb:multiply(?CAc, ?Cb, ?Ch) →

AC(?C, ?CAc)

Rule-1-2_Volume_Of_Concrete_Column

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_Weight_Of_Concrete_Column

Column(?C) ∧ Concrete(?Con) ∧ Volume(?C, ?CV) ∧ Density(?Con, ?CD) ∧ swrlb:multiply(?CW, ?CV, ?CD) →

Weight(?C, ?CW)

Rule-1-4_Cross-section_Area_Of_Reinforcing_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_Ultimate_Axial_Load_Capacity_Of_Concrete_Column

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-1-6_Defining_Structural_Validated_Design

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) ∧ swrlb:greaterThanOrEqual(?CNed, 4500000) →

StructuralValidatedDesign(?C, "validated")

Rule-2-1_Total_Embodied_CO2e_of_Single_Column

Column(?C) ∧ Weight(?C, ?CW) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ EmbodiedCO2e(?Con, ?ECO2) ∧

swrlb:multiply(?TECO2, ?CW, ?ECO2) →

TotalECO2e(?C, ?TECO2)

Rule-2-2_Total_Embodied_Energy_Of_Single_Concrete_Column

Column(?C) ∧ Weight(?C, ?CW) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ EmbodiedEnergy(?Con, ?EE) ∧

swrlb:multiply(?TEE, ?CW, ?EE) →

TotalEEnergy(?C, ?TEE)

Rule-2-3_Defining_Suitable_Exposure_Class_XC1

SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ swrlb:greaterThanOrEqual(?Confck, 25)

∧ Cover(?C, ?CC) ∧ swrlb:greaterThanOrEqual(?CC, 15) →

isExposedTo(?C, XC1)

Rule-2-4_Defining_Suitable_Exposure_Class_XC2

SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ swrlb:greaterThanOrEqual(?Confck, 30)

∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?CCo, 25) →

isExposedTo(?C, XC2)

Rule-2-5_Defining_Suitable_Exposure_Class_XC34

SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ fck(?Con, ?Confck) ∧ swrlb:greaterThanOrEqual(?Confck, 50)

∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?CCo, 15) →

isExposedTo(?C, XC34)

Rule-2-6_Defining_Fire_Resistance_Time_60_for_Square_Column

SquareColumn(?C) ∧ b(?C, ?Cb) ∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?Cb, 200) ∧

swrlb:greaterThanOrEqual(?CCo, 25) →

FireResistanceTime(?C, 60)

Rule-2-7_Defining_Fire_Resistance_Time_90_for_Square_Column

SquareColumn(?C) ∧ b(?C, ?Cb) ∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?Cb, 200) ∧

swrlb:greaterThanOrEqual(?CCo, 31) →

FireResistanceTime(?C, 90)

Rule-2-8_Alternative_Defining_Fire_Resistance_Time_90_for_Square_Column

SquareColumn(?C) ∧ b(?C, ?Cb) ∧ Cover(?C, ?CCo) ∧ swrlb:greaterThanOrEqual(?Cb, 300) ∧

swrlb:greaterThanOrEqual(?CCo, 25) →

FireResistanceTime(?C, 90)
Rule-2-9_Totla_Cost_of_Square_Column *SquareColumn(?C) ∧ Volume(?C, ?CV) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ Cost(?Con, ?ConCost) ∧* *swrlb:multiply(?TCost, ?CV, ?ConCost) →* *TotalCost(?C, ?TCost)*
Rule-3-1_Defining_Suitable_Supplier *ResourceSupplier(?RS) ∧ Rating(?RS, "Very Good") ∧ hasManufacturingSite(?RS, ?MS) ∧ ManufacturingSite(?MS) ∧* *Distance(?MS, ?CD) ∧ swrlb:lessThan(?CD, 200) →* *SuitableSupplier(?RS, "Yes")*
Rule 4-1 Responsible sourcing tier level and points for Excellent product *SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ isSuppliedBy(?Con, ?RS)∧ ResourceSupplier(?RS) ∧ Rating(?RS, Excellent)* *→ TierLevel(?C, 2) ∧ Points(?C, 3.5)*

SQWRL query set

Query-1-1_Count_Cement_Type

Cement(?C) →

sqwrl:count(?C)

Query-1-2_List_All_Cement_Type

Cement(?C) →

sqwrl:select(?C)

Query-1-3_Count_Concrete_Type

Concrete(?C) →

sqwrl:count(?C)

Query-1-4_List_All_Concrete_Type

Concrete(?C) →

sqwrl:select(?C)

Query-1-5_Select_Concrete_With_Cube_Test_Strength_Greater_Than_35

Concrete(?C) ʌ fck(?C, ?f) ʌ swrlb:greaterThan(?f, 35) →

sqwrl:select(?C, ?f)

Query-1-6_Select_Concrete_With_Strength_Class_Greater_Than_C35_and_Embodied Energy_Less_Than_0.95

Concrete(?C) ʌ fck(?C, ?f) ʌ swrlb:greaterThan(?f, 35) ʌ EmbodiedEnergy(?C, ?EE) ʌ swrlb:lessThan(?EE, 0.95) →

sqwrl:select(?C, ?f, ?EE)

Query-2-1_Selecting_Square_Columns_With_Load_Capacity_Larger_Than_4500KN

SquareColumn(?C) ʌ hasConcrete(?C, ?Con) ʌ Concrete(?Con) ʌ h(?C, ?Ch) ʌ b(?C, ?Cb) ʌ Ned(?C, ?CN) ʌ

swrlb:greaterThan(?CN, 4500000) →

sqwrl:select(?C, ?Ch, ?Cb, ?CN)

Query-2-2_Selecting_Validated_Structural_Design

SquareColumn(?C) ʌ StructuralValidatedDesign(?C, "validated") →

sqwrl:select(?C)

Query-2-3_Selecting_Square_Column_with_Size_Constraint

SquareColumn(?C) ʌ hasConcrete(?C, ?Con) ʌ Concrete(?Con) ʌ h(?C, ?Ch) ʌ b(?C, ?Cb) ʌ

StructuralValidatedDesign(?C, "validated") ʌ swrlb:lessThan(?Ch, 420) ʌ swrlb:lessThan(?Cb, 450) →

sqwrl:select(?C, ?Ch, ?Cb, ?Con)

Query-2-4_Selecting_Square_Clolumn_with_Material_Constraint

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

StructuralValidatedDesign(?C, "validated") ∧ swrlb:lessThan(?Ch, 420) ∧ swrlb:lessThan(?Cb, 450) ∧

swrlb:greaterThanOrEqual(?Confck, 35) →

sqwrl:select(?C, ?Ch, ?Cb, ?Con, ?Confck)

Query-2-5_Selecting_Square_Columns_Using_C2835_With_Load_Capacity_Larger Than_4500KN

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

TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧ StructuralValidatedDesign(?C, "validated") →

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

Query-2-6_Selecting_All_Square_Columns_With_Load_Capacity_Larger Than_4500KN

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

StructuralValidatedDesign(?C, "validated") ∧ TotalCost(?C, ?TCost) →

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

Query-2-7_Selecting_Square_Column_Suitable_for_XC1_Class

SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ isExposedTo(?C, XC1) →

sqwrl:select(?C, ?Ch, ?Cb, ?Con)

Query-2-8_Selecting_Square_Column_Having_Fire_Resistance_Time_60_Minutes

SquareColumn(?C) ∧ hasConcrete(?C, ?Con) ∧ Concrete(?Con) ∧ h(?C, ?Ch) ∧ b(?C, ?Cb) ∧ FireResistanceTime(?C, ?CFRT) ∧

swrlb:greaterThanOrEqual(?CFRT, 60) →

sqwrl:select(?C, ?Ch, ?Cb, ?Con)

Query-2-9_Holistic_Design_of_Square_Column

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

Cover(?C, ?CCo) ∧ TotalECO2e(?C, ?TEC) ∧ TotalEEnergy(?C, ?TEE) ∧ TotalCost(?C, ?TCost) ∧

StructuralValidatedDesign(?C, "validated") ∧ isExposedTo(?C, XC1) ∧ FireResistanceTime(?C, 60) →

sqwrl:select(?C, ?Ch, ?Cb, ?Con, ?CCo, ?Confck, ?TEE, ?TEC, ?TCost)

Query-3-1_Selecting_Supplier_of_Aggregates

ResourceSupplier(?RS) ∧ CompanyName(?RS, ?CN) ∧ CertificateNo(?RS, ?CEN) ∧ Rating(?RS, ?CR) ∧ PostCode(?RS, ?PC) ∧

hasManufacturingSite(?RS, ?MS) Λ ManufacturingSite(?MS) Λ Address(?MS, ?CA) Λ Distance(?MS, ?CD) Λ *isSupplierOf(?RS, ?Agg) Λ Aggregate(?Agg) →* *sqwrl:select(?RS, ?CN, ?CEN, ?CR, ?CA, ?PC, ?CD)*
Query-3-2_Selecting_Supplier_of_Reinforcement *ResourceSupplier(?RS) Λ CompanyName(?RS, ?CN) Λ CertificateNo(?RS, ?CEN) Λ Rating(?RS, ?CR) Λ PostCode(?RS, ?PC) Λ* *hasManufacturingSite(?RS, ?MS) Λ ManufacturingSite(?MS) Λ Address(?MS, ?CA) Λ Distance(?MS, ?CD) Λ* *isSupplierOf(?RS, ?Agg) Λ Steel(?st) →* *sqwrl:select(?RS, ?CN, ?CEN, ?CR, ?CA, ?PC, ?CD)*
Query-3-3_Selecting_Supplier_of_Concrete_Product *ResourceSupplier(?RS) Λ CompanyName(?RS, ?CN) Λ CertificateNo(?RS, ?CEN) Λ Rating(?RS, ?CR) Λ PostCode(?RS, ?PC) Λ* *hasManufacturingSite(?RS, ?MS) Λ ManufacturingSite(?MS) Λ Address(?MS, ?CA) Λ Distance(?MS, ?CD) Λ* *isSupplierOf(?RS, RC40_50_5) →* *sqwrl:select(?RS, ?CN, ?CEN, ?CR, ?CA, ?PC, ?CD) Λ sqwrl:orderBy(?CD)*
Query-3-4_Selecting_Suitable_Supplier_for_Concrete *ResourceSupplier(?RS) Λ SuitableSupplier(?RS, "Yes") Λ CompanyName(?RS, ?CN) Λ CertificateNo(?RS, ?CEN) Λ* *Rating(?RS, ?CR) Λ PostCode(?RS, ?PC) Λ isSupplierOf(?RS, RC40_50_5) →* *sqwrl:select(?RS, ?CN, ?CEN, ?CR, ?PC)*