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An Ontology-based Approach Supporting Holistic Structural Design with the consideration of safety, environmental impact and cost

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Abstract. Early stage decision-making for structural design critically influences the overall cost and environmental performance of buildings and infrastructure. However, the current approach often fails to consider the multi-perspectives of structural design, such as safety, environmental issues and cost in a comprehensive way. This paper presents a holistic approach based on knowledge processing (ontology) to facilitate a smarter decision-making process for early design stage by informing designers of the environmental impact and cost along with safety considerations. The approach can give a reasoning based quantitative understanding of how the design alternatives using different concrete materials can affect the ultimate overall performance. Embodied CO_2 and cost are both considered along with safety criteria as indicative multi-perspectives to demonstrate the novelty of the approach. A case study of a concrete structural frame is used to explain how the proposed method can be used by structural designers when taking multi performance criteria into account. The major contribution of the paper lies on the creation of a holistic knowledge base which links through different knowledge across sectors to enable the structural engineer to come up with much more comprehensive decisions instead of individual single objective targeted delivery.

Keywords: Holistic Structural Design, Ontology, Environmental Impact, Lifecycle Cost, Multi-Criteria Decision Support

1. Introduction

It is commonly acknowledged that human activities have been promoting climate change; this, in turn influences our daily life, including the environment, economies, and societies. The building and construction sector constitutes a significant portion of the total energy and global greenhouse gas emissions – more than any other sectors [1]. In the UK, buildings are responsible for more than 40% of the country's total energy consumption and release approximately 300 million tons of CO_2 each year [2]. Indeed, it is obvious that efforts in building sector can contribute to the reduction of the threat of climate change since it has the largest potential for reducing environment impact [3].

A building project is chronologically composed of three main stages, namely the design, construction, and use phases. The potential for influencing environmental impact and cost performance is very high in the design stage, and decreases dramatically with the progression of time [4]. This means that a large number of building decisions are made by designers in the

early phase, and this critically determines a building's ultimate performance [5]. Structural engineers, as a key part of the design team, work alongside architects and MEP (mechanical, electrical, plumbing) engineers to ensure that buildings are strong enough to withstand all kinds of loads and actions. During the building design process, structural engineers normally pay more attention to safety and technical issues than environmental impact and cost concerns; this is because decisions related to this aspect largely hinge on the architect and client, which means that their contribution to the environmental performance is negligible [6]. Recent years have witnessed an increased awareness of the fact that structural engineers can make significant contributions to the reduction of environmental impact and cost. However, this is only possible if they pay a great deal of attention to the sustainability and cost, because a large amount of structural material is used in structures [7,8]. For example, Kaethner and Burridge [9] investigated the embodied carbon of building structures and demonstrated that the structure represents the largest weight and contributes to over half of the embodied carbon emissions in office buildings. Webster [10] performed life-cycle assessment (LCA) studies of the wood-framed, concrete-framed high-rise buildings and steel buildings. The research highlighted the view that the structural system in a range of structure types can contribute a significant proportion of the life-cycle environmental impact. They estimated that reducing structural greenhouse gas (GHG) emissions by 50% on all new buildings would be equivalent to taking 11 million new cars driven. This equals an 8% reduction in total U.S. automobile use and a 4% reduction in U.S. total emissions. Further, they also estimated that reducing structural construction and demolition (C&D) waste by 50% would reduce the total C&D waste stream by at least 25%-that is 20 million metric tons. A survey conducted by Miller et al. [7] showed that the average estimation of the contribution of embodied energy to a structures life cycle consumption was 28.4%. Additionally, attention must be paid to the various indirect benefits of structural design, such as increasing the overall net area and net height, improving lifespan, shortening the construction schedule, and reducing labor and equipment. All of these factors influence overall performance with regard to environmental impact and cost.

However, despite this growing awareness, structural engineers commonly fail to combine environmental issues and cost into a holistic structural design. This is due to the fact that, in practice, a number of barriers exist [11]. Firstly, for a structural engineer, knowledge of sustainability is fragmented and distributed in different formats. Structural engineers may experience confusion in terms of which parts of the sustainability-related context need to be considered and how environmentally efficient building material and elements can be incorporated into the design of a given structure. For example, and much the same as the layout of a concrete structure, the material choice for the structural frame includes: normal strength concrete (NSC), high-performance concrete (HPC), ultra-high performance concrete (UHPC) and the above three materials with supplementary cementitious materials (SCMs). It is unclear as to how these choices will affect the environmental impact and cost performance of a whole structure. Secondly, there are insufficient regulations and sustainable tools available for structural engineers to quantify the environmental impact and the cost of the structure at early stages. BREEAM, LEED, and Australia's Green Star rating system provide more opportunities to facilitate sustainable design by marking the whole building at the later design stage. However, this is designed for decision making by architects rather than structural engineers. Thirdly, policymakers, owners, and key stakeholders are unaware of the important role that a structural engineer can play; this means that they lack financial incentives and rewards to incorporate sustainability. Under these circumstances, there is an urgent need to develop a holistic design approach to facilitate holistic structural design by informing the structural engineer the impact of their design decisions on the safety, sustainability, cost and other aspects of the building/infrastructure structure.

As one of the emerging Semantic Web technologies, ontology is widely used for knowledge sharing and reuse across different domains; it has great potential to address the problems related to holistic structural design. Ontology has many attractive features [12, 13], which include: (1) It provides a vocabulary and a framework through which to structurally model knowledge of a given domain in a format that can be processed by both machine and human. (2) It not only defines the terms in a specific domain, but also describes the relationships between these terms in various domains. (3) It provides a hierarchy of concepts in a particular domain. Because of the above advantages, it is expected that ontology could be used as a tool to develop a holistic structural design tool. However, in the field of structural design, more advanced deductive reasoning capability is required due to the existence of a large number of calculations. In order to extend the flexibility of ontology and meet the requirements of structural design, an effective and robust tool on top of ontology is needed for more specific calculation purposes. As such, semantic web rule language (SWRL) is employed in this research.

Furthermore, the appearance of up-to-date material offers more opportunities for an engineer to design a lightweight, aesthetic, long-lasting structure. For example, HPC can be used to reduce slab volume, which in turn reduces the building's overall weight; this slims the columns and increases the overall net area [14]. The sustainability benefit of HPC – namely that it uses less material – is further underlined by the possibility of using by-products from other industries such as fly ash (FA), ground granulated blast furnace slag (GGBS), and limestone powder(LP) [15]. Similarly, the new generation of UHPC offers significant potential for producing even small/thinner structural elements. However, given the recognised benefits of high-performance concrete, it is surprising that its use is not more widespread. This can be attributed to the lack of holistic structural design method and structural engineers' unfamiliarity with HPC and UHPC. As an initial attempt, the present paper incorporates three kinds of concrete into SCMs to create an alternative material for multi-perspective structural design.

The focus of this research is to create a feasible way to help structural engineers to achieve much more comprehensive structural designs at the early design phase. The proposed approach combines sustainability and cost with safety knowledge to inform structural engineers of the environmental impact and cost performance of a structure depending on their choice of different material. Emphasis lies on the effect of structural elements and materials, which means that the non-structural elements and material are not incorporated in this work. An ontology-based decision support system is constructed to provide optimised design solutions to not only reduce embodied carbon and cost, but also to offer an alternative to structural feasibility. The structure of this paper is introduced as follows: Section 2 presents a brief review for sustainable concrete structural design and ontology, followed by a detailed procedure for design and development of structural design ontology in Section 3. A case study of a structure frame is demonstrated and validated in Section 4. Finally, Section 5 gives the main conclusions of this study.

2. Literature review

2.1 Review of sustainable structural design

Much attention has been paid to emphasize the importance of architectural design in the early stage of the whole building performance. Many methods have been developed for the design of environmentally optimal buildings [16-19]. However, only a few studies have been devoted to structural design in terms of sustainability. For example, Kohler and Moffatt. [4] highlighted that, in the early design phase, the possibility of influencing the performance of environmental impacts and the cost of a building is relatively high. They suggested that at the early design

stage the whole design team can involve in a workshop with the aim of providing the optimal design solutions. Similarity, Borchers [20] underlined the importance of structural engineering in sustainable and low carbon design. They mentioned that in the UK, construction materials make up more than 25% of the total national gas emissions and great potential exists for structural engineering to control CO_2 emissions during the early design phase.

Several researchers have studied the embodied CO_2 emissions and cost from a structural element level (i.e., beam, slab, column). For example, Hájek et al. [21] applied LCA methodology to assess the performance of the concrete slab. Three structural floor alternatives ranging from NSC to HPC were chosen for the environmental assessment. They suggested that when evaluating the environmental impacts of a concrete structures, a detailed and uniform LCA is greatly demanded. Yeo and Gabbai [22] performed a study for optimizing a simple reinforced concrete beam with the fixed moment and shear strengths in terms of sustainable design. The results indicated that in order to reduce 10% of the embodied energy of a beam, the cost will increase 5% accordingly. A further study [23] by Yeo and Potra presented an optimization approach for a structural engineer to evaluate the sustainability and economic objectives. A reinforced concrete frame was used as a case to illustrate the proposed approach. The results indicate the developed approach can reduce carbon emission by 5% to 15%.

Other researchers investigated the embodied CO_2 or cost from a whole structure scale. Kaethner and Burridge [9] compared the embodied CO_2 of different type of buildings, such as commercial, hospital and school buildings. They concluded that the concrete framed structure showed similar levels of CO_2 compared to steel framed buildings. A study undertaken by Guggemos and Horvath [24] showed the comparison of environmental effects between concrete and steel-framed structure during the construction stage. Their results indicated that the concrete frame use more energy, while the steel frame show high level of metal emissions. Foraboschi et al. [25] studied the embodied energy of tall building structures in range of 20 to 70 stories. The results indicated that the lowest weight of a structure does not necessarily mean it has the lowest embodied energy. The embodied energy largely depends on what type of slab used in a structure. They also concluded that steel structure consumes more embodied energy compared to that of a reinforced concrete structure.

There are some previous studies devoted to discusses the methodologies for the sustainable structural design. For instance, Danatzko and Sezen [26] investigated five sustainable structural design methodologies: (1) Minimizing Material Use; (2) Minimizing Material Production Energy; (3) Minimizing Embodied Energy; (4) Lifecycle Analysis/Inventory/Assessment; (5) Maximizing Structural Systems Reuse. Another classification, proposed by Anderson and Silman [27] focused on strategies which aimed at reducing the carbon footprint of building structures: (1) Design for Materials, (2) Design for Recycling, (3) Design for Efficiency, (4) Design for Energy, and (5) Design for Adaptability. This classification overlaps and partially integrates with the classification of Danatzko and Sezen [26]. The latest review on sustainable structural design was conducted by Pongiglione and Calderini [28]. They identified that main features and steps for conducting a sustainable structural design, which includes the targeted impacts, strategies and parameters. The strategies involve: (1) Durability; (2) Adaptability; (3) Reuse; (4) Design for reuse and recycling; (5) Low-carbon or low-energy materials; (6) Material minimization; (7) Minimizing energy use; (8) Attention to human health; (9) Lifecycle assessment. Further, Bakhoum and Brown [29] proposed the sustainability criteria related to structural materials by developing a sustainable scoring system. The system includes a list of sustainable factors that affect the process of structural materials selection. However, the above

methodologies are generally used as guidelines or benchmarks for sustainable structural design, providing no detailed guidance over the design process.

In an effort to automate the performance of a sustainable structural design, some researchers have integrated sustainability issues into Building Information Modelling (BIM) or extracted BIM information for the sustainable assessment. For instance, Oti and Tizani [30] utilized principle of feature-based modelling to extract the BIM model information with the aim of sustainable analysis in the early stage of structural design. A further review by Oti et al. [31] summarize the methods of using API in BIM extension for the purpose of sustainability analysis. They also demonstrated an API application in BIM for the sustainable appraisal by using a case study of steel structure design. Eleftheriadis et al. [32] proposed an optimization framework by combining BIM (Revit), LCA tool (Tally) and structural analysis (Robot) for environmentally structural design. The case study was a simple steel-framed structure with 5m width, 5m length and 3m height. The results showed that their approach demonstrates 21% savings in the indicators such as GWP, compared to the standard UK catalogue steel sections. A further review by Eleftheriadis et al. [33] presented the recent developments of BIM-based design processes in both life cycle energy and the structural engineering domain. The study identified the potential contribution of BIM in the sustainability domain and pointed out that holistic engineering approaches that combine the technical, environmental and economic performance of a building over its whole life cycle are still underdeveloped. Despite the above pioneering work have been conducted towards integration of sustainability into BIM, these methods often suffer from duplicate entries, data loss and amount of time required for format conversion among different software. Generally accepted and integrated methodology available to conduct sustainable structural design have not been addressed sufficiently in the literature, which means that there is no single approach that can address a holistic sustainable structural design. There is still plenty of scope for further investigation in this area.

From the above literature, it can be inferred that structural design can be seen to have an important impact both on building costs and on embodied carbon, and considerable potential exists for reduction as a result of choosing alternative design structures. However, these studies might not sufficiently provide a universal approach of structural design with combined consideration of safety, environmental impact and cost in a comprehensive way. Some of these studies only focus on one aspect of sustainability or cost (i.e., a beam or a slab), while others simply concentrate on the calculation of the environmental impact of different buildings for comparison purposes. Although the research interest shifts towards integration of sustainability into BIM, there is scant evidence that sustainability has been systematically considered as an integral part of the BIM collaborative process. While in theory, nD modelling has been made possible by the technological advancements, in practice it has not been effectively implemented in a holistic way. More commonly accepted aspects of BIM-enabled sustainable design have not been addressed sufficiently in the literature. Therefore, it is imperative to have a holistic decision supporting approach that integrates structural design knowledge, sustainability and cost information to inform structural engineers of the environmental impact and cost performance of a building among different material choices.

2.2 Review of ontology in construction sector

Researchers are examining ontology as a new semantic web technology because of increasing demands for better knowledge management, information integration and interoperability. Ontology's most important advantages are its ability to share information between people and/or software, and the ability it gives to reuse domain knowledge. More importantly, the

semantic interoperability among different domains offers more opportunity in decision-making and it is easy to be further extended to collaborate with other software systems.

Numerous literature has been collated on the exploration and implementation of ontology, which ranges from medicine, biology, transportation and agriculture to economy. In the building construction sector, ontologies are used to assist the information exchange and sharing, such as education, compliance checking, project management, facility management, and sustainability. Ahmed et al. [34] proposed an ontology model for sharable learning objects in construction management. Yurchyshyna and Zarli [35] proposed a framework based on the ontology to check conformance issues and developed an ontological method to semi-automatically check the conformity in construction sector. Abanda et al. [36] proposed an ontological approach for house-building labour cost estimations and further conducted a comprehensive review on how to continue movement away from traditional construction applications and towards information-intensive applications and knowledge that is grounded in the semantic web. Dibley et al. [37] developed an ontology to facilitate real-time monitoring of a building based on a multi-objective framework. Schevers et al. [38] used the industry foundation class (IFC) and Semantic Web technology for digital facility modeling of the Sydney Opera House. In the structural design field, Hou et al. [39] are probably the first who applied the ontology in structural design for decision making. However, their approach only considered a single column with different embodied emission and CO_2 options rather than considering these structural elements (e.g. beam, column, footings) from a whole structure scale.

It is worth mentioning that ontologies are used to promote the information exchange and sharing in the BIM domain. For instance, Ding et al. [40] developed an ontology-based methodology to facilitate the construction risk knowledge management. A case study is implemented to show how to identify risk factors, reason risk paths and prevent risk. Park et al. [41] developed a conceptual system by integrating the ontology with BIM for construction defect management, which can reduce the defect occurrence during the construction process. The results showed that this method can improve the effectiveness of the current defect management. Terkaj and Šojić [42] presented an enhancement of conversion patterns to convert IFC to Web Ontology Language (OWL) by adding class expressions. This method can improve information consistency and applicability for the industrial application. Lee et al. [43] proposed a novel methodology for the defect management domain by combining BIM and ontology, which can reduce the defect occurrence and thus improve the defect management. Venugopal et al. [44] developed an ontological framework that based on the field of the precast concrete industry. The approach can reduce the development time of constructing models and make model view specifications more clear. A construction safety ontology developed by Zhang et al. [45] formalised knowledge of safety management through development of three domain ontology models, namely the construction product, process and safety model. The developed ontology models can be linked to BIM for the automated safety planning. In the

Based on the review of ontology applications in the construction sector, several conclusions can be obtained as follows: (1) Despite many applications in the construction sector, much of the ontology developments remain at the conceptualisation of domain knowledge, which means that there still exists a gap between the theory and practical use. (2) The potential of the Semantic Web, such as reasoning, are not maximized in those applications that limit the development of more efficient and heavyweight ontology. (3) Although sustainability issues are partially considered in some domain ontologies, few works have been conducted on sustainable design development, especially in the structural design domain. In the following

section, it will demonstrate how to integrate structural design, sustainability and cost with ontology to facilitate decision-making in the structural design.

3. Design and development of structural design ontology

3.1 Underlying resources for ontology development

3.1.1 Existing related concrete sustainability performance database

In this work, three types of concrete are selected, namely NSC, HPC and UHPC and these three with SCMs. They each consist of three concrete classes. The NSC covers the C25, C35 and C45 classes. The mix proportion for NSC is designed conforming to BS EN206-1 [46]. For example, 1 m^3 of C28/35 concrete comprised 300 kg of cement, 1915 kg of aggregate and 165 kg of water. The HPC includes the C80, C90 and C100 classes. The mix design of HPC is different from that of NSC because of the addition of silica fume (SF) and superplasticizer (SP). The mix proportion for HPC was designed according to available literature [47, 48], which is based on several experimental results. Finally, UHPC has ultra-high strength and outstanding performance due to the use of superplasticizer, low water to cement ratio, highly fine sand and absence of coarse aggregate, which includes the C160, C170 and C180 classes. Since there is no commonly accepted mix proportion for UHPC and limited information on this, the mix design of UHPC is based on several previous literatures [49-51]. For instance, to obtain a compressive strength of 180 Mpa, 1 m^3 of UHPC normally consists of 900 kg of cement, 1016 kg of sand, 185 kg of water, 225 kg of silica fume and 28.2 kg of superplasticizer. Moreover, to minimize the environmental impact of concrete, SCMs are added in each type of concrete to replace cement by a different replacement level. The replacement levels for FA, GGBS and LP are 10-30%,10-50% and 5-15%, respectively.

3.1.2 CO_2 evaluation procedure

Most commonly, an embodied CO_2 footprint for concrete can be estimated by the simple method [52]:

$$CO_2 = CO_{2-M} + CO_{2-T} + CO_{2-C} \qquad (1)$$

where CO_{2-M} represent the CO_2 emissions in the material production, CO_{2-T} and CO_{2-C} refer to the emissions from transportation and construction stage. Since the concrete includes cement, water, aggregate, SF, SP and SCMs, the CO_{2-M} can be obtained through:

$$CO_{2-M} = \sum_{i=1}^{n} W_i \times CO_{2-i} \qquad (2)$$

where i is a kind of material, n represents the number of material in concrete, and W_i and CO_{2-i} represent the specific weight (kg/m^3) and CO_2 emission (CO_2 kg/kg). The CO_2 emission for each material in concrete is calculated based on the ICE database and reference papers [53-55]. For the abovementioned concrete with SCMs, it should be noted that the k-value for FA, GGBS and LP is 0.4,0.6 and 0.5 [56], respectively. This not only means that the k-value represents the percentage equal to the cement, but also means that the amount of these materials should be multiplied by 1/0.4,1/0.6 and 1/0.5 when calculating their CO_2 footprint. For example, the CO_2 footprint for FA is 0.004 kgCO_2 /m^3. To obtain the same concrete strength, the amount of FA used is 2.5 times greater than that of the cement amount and thus should be multiplied by 2.5

when calculating their dosage in the concrete. The same calculation method is applied to GGBS and LP.

To obtain the whole embodied environmental impact, the CO_2 from transporting and on-site construction needs to be considered, which is shown as follows:

$$CO_{2\text{-T}} = \sum_{i=1}^{n} W_i \times CO_{2-i(T)} \times D_i \qquad (3)$$

where D_i is the transportation distance (from the concrete factory to the construction site) for 1 m^3 of the freshly concrete. $CO_{2-i(T)}$ is the CO_2 emission from the concrete mixer truck per cube concrete. It is assumed that the distance is 30 km from the concrete factory to the site. The $CO_{2-i(T)}$ for 1 m^3 of the freshly produced concrete is 0.674 kg CO_2 /m^3 • km. Moreover, since the concrete is normally cured by allowing it to air-dry or by water, the $CO_{2\text{-C}}$ in the construction phase is neglected in this work.

3.1.3 Cost evaluation procedure

The cost evaluation can be conducted by a simple method using the following equation:

$$\text{Cost} = \sum_{i=1}^{n} W_i \times Cost_i \qquad (4)$$

where W_i is the unit volume weight (kg/m^3), $Cost_i$ represent the cost per kg US dollar ($US /kg). It should be noted that the cost of a building contains labour, equipment and materials. Due to the limited research time, it is unnecessary to incorporate all these factors into the ontology. As an initial attempt, only the material cost is considered in this study. Based on the above equations and the database, the CO_2 footprint and cost for NSC, HPC and UHPC [50, 57] are calculated and shown in Tables 1 and Table 2, respectively.

Table 1: Underlying data for CO_2 and cost assessment of NSC, HPC and UHPC

| Item | $CO_{2-i(M)}$ | $Cost_i$ | W_i(kg/m³) | | | | | | | | |
| | | | NSC | | | HPC | | | UHPC | | |
	(kgCO₂/kg)	($US/kg)	C25	C35	C45	C80	C90	C100	C160	C170	C180
CEM I 32.5	0.930	0.22	260	300	340	–	–	–	–	–	–
CEM I 52.5	0.476	0.25	–	–	–	510	580	650	790	845	900
Aggregate	0.004	0.015	1955	1915	1875	1673	1600	1526	1016	1016	1016
Water	0.0003	–	165	165	165	165	165	165	185	185	185
Silica fume	0.014	0.6	–	–	–	27	30	34	195	210	225
Superplasticizer	0.944	4.78	–	–	–	15.4	15.4	15.4	28.2	28.2	28.2
Steel	1.86	0.6									
CO₂-M (kg CO₂ /m³)			249	286	324	264	297	330	462	491	519
CO₂-T (kg CO₂ /m³)			20	20	20	20	20	20	20	20	20
CO₂ (kg CO₂ /m³)			269	306	344	284	317	350	482	511	539
Cost ($US/m³)			87	95	103	242	260	279	465	487	510

Table 2: Underlying data for CO_2 and cost assessment of NSC, HPC and UHPC with SCMs

Item	CO$_2$ (kgCO$_2$ /m^3) Cost ($US/m^3)	FA (0.004 kgCO$_2$ /m^3 0.046 $US/m^3)			GGBS (0.052 kgCO$_2$ /m^3 0.10$US/m^3)			LP (0.032 kgCO$_2$ /m^3 0.122$US/m^3)		
		10%	20%	30%	10%	30%	50%	5%	10%	15%
C25	CO$_2$	245	221	198	247	203	160	258	247	235
	Cost	84	81	78	85	82	80	87	87	87
C35	CO$_2$	279	251	224	281	230	180	294	280	267
	Cost	92	88	85	93	90	87	95	95	96
C45	CO$_2$	312	281	250	315	257	200	329	314	300
	Cost	99	96	92	101	97	94	103	104	104
C80	CO$_2$	260	236	213	264	224	185	274	263	253
	Cost	236	229	222	238	230	221	242	242	242
C90	CO$_2$	290	263	236	295	250	204	305	293	282
	Cost	253	245	237	256	246	236	260	260	260
C100	CO$_2$	320	290	260	325	275	224	337	324	310
	Cost	271	262	253	274	263	252	279	279	279
C160	CO$_2$	440	398	356	447	377	307	463	445	426
	Cost	454	443	433	458	445	431	464	464	464
C170	CO$_2$	466	421	376	473	398	324	491	471	451
	Cost	476	464	453	480	466	452	487	487	487
C180	CO$_2$	492	444	396	500	420	341	518	497	476
	Cost	498	486	474	502	487	472	510	509	509

3.2 System framework

The developed ontology system consists of four essential segments: knowledgebase, ontology management system, rules editor and query interface. The knowledgebase is the crucial component since the ontology and structural design knowledge are saved in the form of an OWL file. Protégé-OWL 5.1 is employed as the ontology management system providing ontology and rule editing, SWRLTab plug-ins, reasoners and other functions are required for prototype system development. The query interface is a platform used by a structural engineer to interact with the knowledge management system. The workflow can be explained as follows: (1) The knowledge engineer converts the structural design, sustainability and cost knowledge into ontology and SWRL rules; (2) Knowledgebase stores the ontology and SWRL rules that are edited through Protégé main interface and SWRLTab. (3) The rule engine in ontology management system runs the SWRL rules and generates new facts for the knowledgebase; (4) The end user (e.g., structural engineer) obtains possible results by inputting the design demands from SQWRL query interface (SQWRLQueryTab). The role and task of the "Knowledge engineer" is ontology development, which includes two main steps. In the first step, a comprehensive list of all the concepts related to sustainability and structural design is identified and generated. For example, the values of embodied carbon, cost and basic equations of the structural design are chosen from ICE database, literature and structural design code. In the second step, the knowledge generated from step 1 are converted into ontology and SWRL rules. The software that the knowledge engineer use is an ontology development tool— Protégé-OWL

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5.1 and its plug-in (SWRL Editor and Tab). The role of structural engineer is like an "end user" to interact with the ontology and acquire the possible design solutions. More details of the system are shown in Figure 1.
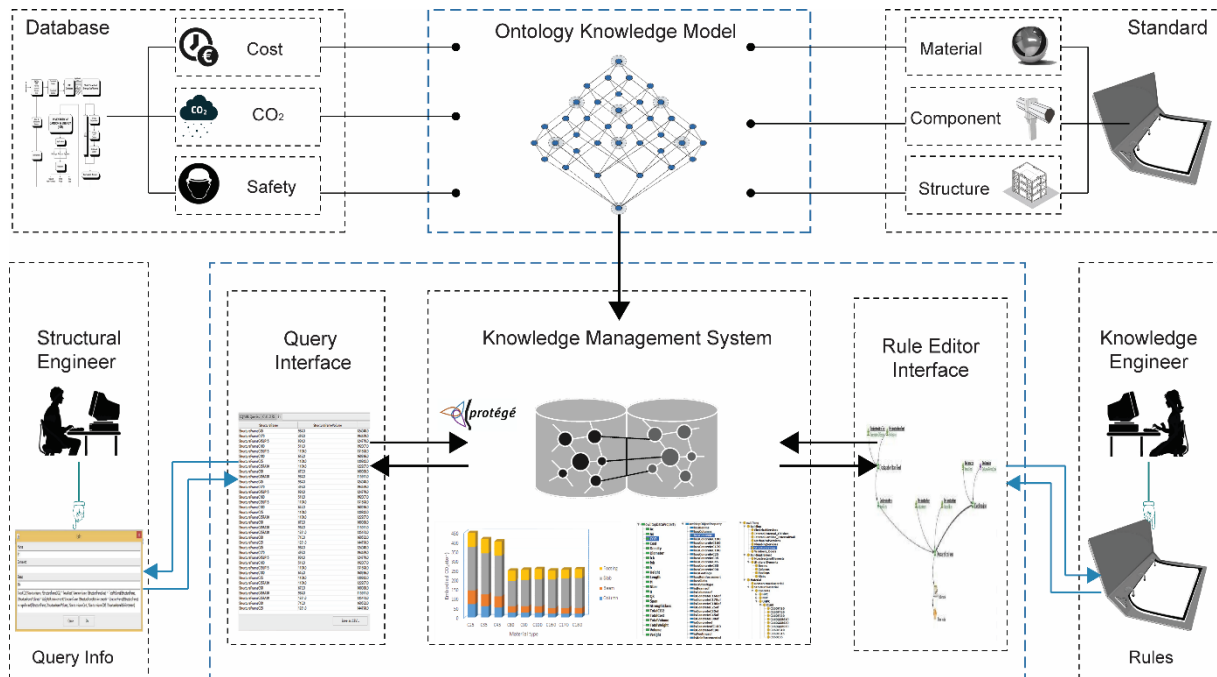

Fig.1 The developed ontology framework

3.3 Ontology development

From the previous literature [58-60], many methodologies can be used for ontology development, such as Uschold and King, Grüninger and Fox, Methontology, KACTUS and Ontology Development 101. Each methodology has its advantages and drawbacks. In this work, Ontology Development 101 is chosen because of the following reasons: (1) It is easy to use for beginners with no former experience of ontology development. (2) It provides guidance on how to implement the ontology step-by-step in the Protégé software environment. (3) It is suitable for development by reusing existing ontologies. Therefore, the following steps are used to construct the structural design ontology:

Step 1. Determine the domain and scope of the ontology

The domain and scope of the ontology can be identified by listing some basic questions (BQ) and competency questions (CQ). Asking these questions early and in easily understood language will test whether there is enough information in the ontology as it stands. For example:

BQ: What is the purpose of building this ontology?

A: To inform structural engineers of different choices and give them a quantitative understanding of how these choices will affect the ultimate environmental impact and cost performance of a building structure.

BQ: What is the domain of the ontology?

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A: Structural design, sustainability and cost.

BQ: Who is the user of the developed ontology?

A: Structural engineers

CQ: What is the structure form?

A: Concrete structural frame.

CQ: What type of structural elements will be covered in this study?

A: Flat, beam, column and footing.

CQ: What kind of concrete will be used in this study?

A: Normal strength concrete with and without SCMs, high performance concrete with and without SCMs and ultra-high performance concrete with and without SCMs.

CQ: How to quantify the sustainability and cost?

A: Embodied CO_2 and $US.

The structural design ontology connects sustainability and cost with safety knowledge for holistic structural design. The schema of the developed ontology is shown in Figure 2.
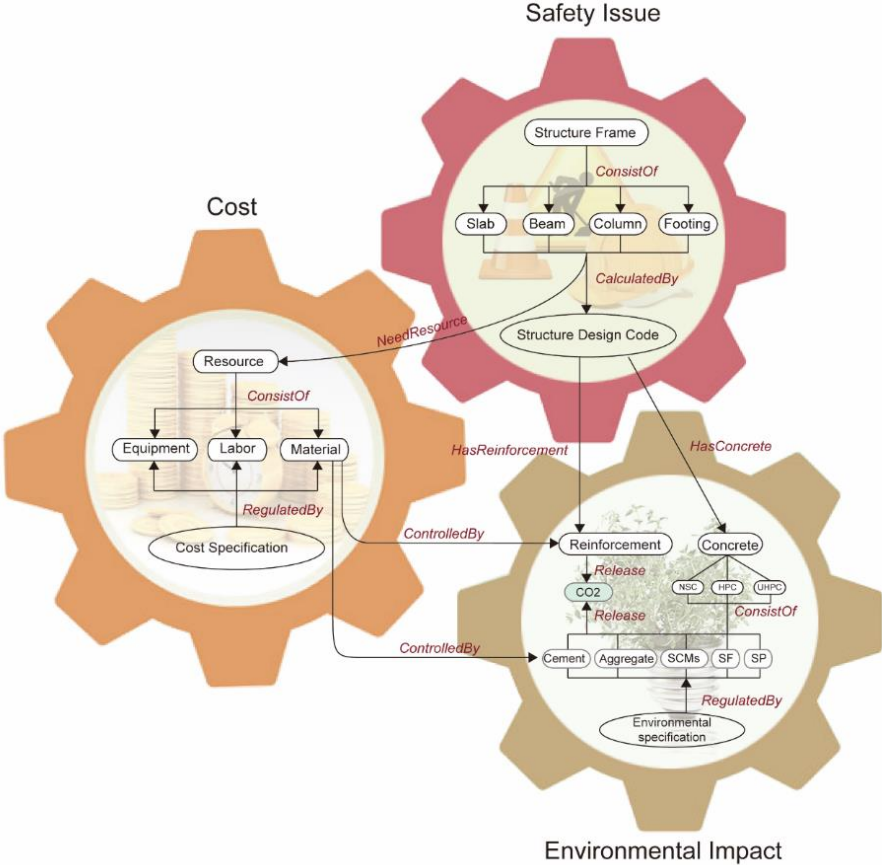
Fig.2 The structural design ontology schema

Step 2. Consider reusing existing ontologies

It is worth considering reusing existing ontologies or extending existing sources for a particular domain when building a new ontology. From the available literature, there are many reusable ontologies. For example, BuildingSMART has constructed an IFC framework which, for building design, is seen as an established standard under which models of building information can be shared and exchanged so that design can be made more effective, with follow-on benefits for construction and operation [61]. Therefore, the developed ontology in this work uses the IFC schema as a reference by adding more specific relationships or modifying their concepts to more readable names. In this ontology, for example, "Column" has been substituted for "ifcColumn".

Step 3. Enumerate important terms in the ontology

Initially, it is essential to generate an inclusive inventory of the entirety of terms that associated with the sustainability, cost and structural design in this step. As introduced in Section 3.1, the underlying data of the CO_2 footprint and cost for NSC, HPC and UHPC are calculated based on the BS EN206-1, ICE database and reference papers, which are shown in Tables 1 and 2, respectively. Taking C35 as an example, 1 m^3 of C35 concrete comprised: 300 kg of cement, 1,915 kg of aggregate, and 165 kg of water. The value of embodied CO_2 for cement (Portland cement, CEM I 32.5), aggregate and water are 0.93,0.005, and 0.0003 kg CO_2 per kg material [54, 62-63], respectively. Therefore, the total embodied CO_2 of C35 can be obtained by:

$$CO_{2\text{-}M} = \sum_{i=1}^{n} W_i \times CO_{2-i} = 300 \times 0.93 + 1915 \times 0.004 + 165 \times 0.0003 = 286 \text{ kg } CO_2 \text{ /m}^3$$

Furthermore, on the whole building level, the building consists of a structural frame, mechanical system, electrical system, plumbing system, internal partition, external wall, windows and doors. Since the purpose of developing the ontology is for structural design, only the structural frame is considered in the ontology. The structural frame comprises structural elements such as a slab, beam, column and footing. All the structural elements cover NSC, HPC and UHPC. The cement, aggregate, water, silica fume, superplasticizer and SCMs comprise of either NSC, HPC or UHPC.

Step 4. Define the classes and the class hierarchy

Defining the classes and properties of them is the primary stage in the ontology-design development. A top-down establishment is constructed, which commences with the definition of the most general classes and subsequent specialization of the classes. Starting with a super-class in which building, building element and material are all combined, this super-class is broken down first into classes and then into sub- classes. The latter are very specific as to what may be included in them. The building element class contains non-structural elements and structural elements sub-classes. The latter contains slabs, beams, columns and footing sub-classes. More detailed classes are shown in Figure 3a.

Step 5. Define the properties of classes

Defining the properties of the concepts and developing the class hierarchy are sometimes intertwined. Normally, the definition of the class is first established and then the properties of the class are described. In terms of the properties, object property, data-type property and

annotation property are mainly three types of properties. Relationships between classes are defined by the object property. An example would be: hasConcrete, and isConcreteOf. Characteristics of instances of each class are defined by the data-type property, and this applies to both quantity and quality. The sort of value types found here include such things as: Number; String; Enumerated; and Boolean. As a simple example, we will take a slab made of the type of concrete classified as "C25." This can be represented in the ontology as: an instance of the slab class where "C25" is the data-type property. Further data values such as volume, reinforcement, cost and CO_2 can then be added. Furthermore, the function of the annotation property is to clarify the data and explanation by inputting a comment on some elements of the ontology wherever it is needed. Figure 3b shows the main classes' properties of the developed ontology.

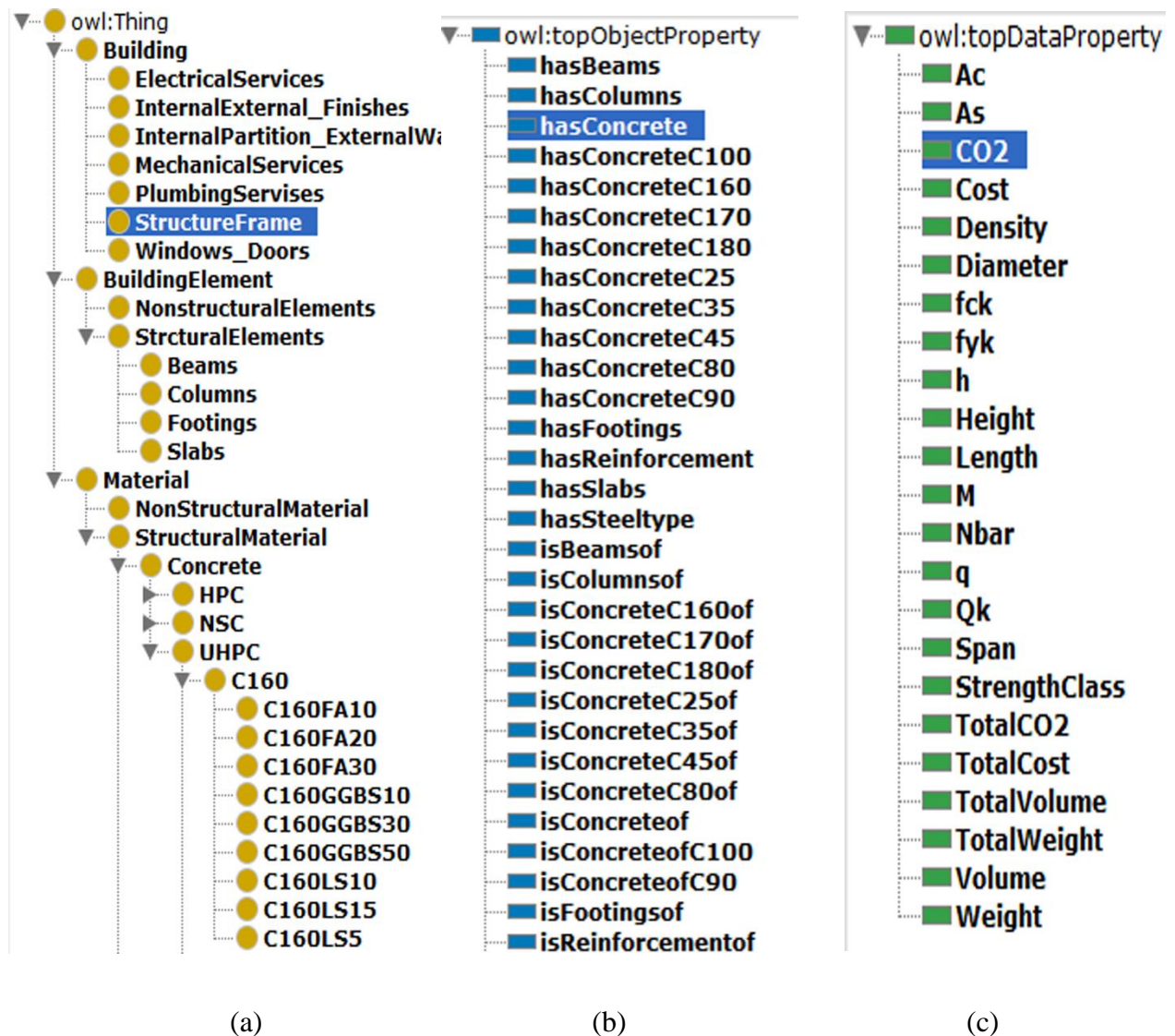(a)   (b)   (c)

Fig.3 The developed ontology in the Protégé-OWL 5.1

Step 6. Create instances

Within classes, individual instances have their own hierarchical place, and the process of defining each individual instance within a class will involve these steps: (1) Choose a class; (2)

Generate an instance for this class; and (3) Populate the values of that specific instance. For example, if a knowledge engineer would like to create a column instance, each step is as follows: (1) Choose a "Column" class from the top class "StructuralElements"; (2) Generating an instance (e.g. columnC25); (3) The values of properties is either manually added or automatically deducted by the SWRL rules predefined by the knowledge engineer. The developed ontology involved totally 109 types of predefined instance, which includes 36 types of column, 36 types of beam, 36 types of slab and one type of footing. Except the footing, all the instance ranging from NSC to UHPC includes the supplementary cementitious materials, namely FA, LP and GGBS. For example, if a structure engineer chooses the concrete class of C35 as the column material, the option includes C35, C35 with addition of FA, C35 with addition of LP and C35 with addition of GGBS. It will be necessary to enter data-type properties manually in some cases, but in the case of others, specific values are not given because SWRL rules deduct them. For example, the span and load of a slab is manually input and regarded as initial facets, while the cross-sectional area, volume, weight and reinforcement are calculated automatically based on the SWRL rules and initial facets, which are regarded as inferred facets. Similarly, embodied CO_2 and cost values appeared in Tables 1 and 2 is presented in the form of data-type properties for the different level types of concrete. There are mainly five data-types that describe the types of values that can define the properties: string, number, boolean, enumeration, and instance-type. For example, concrete strength "f_{ck}" can have a value type of "Float", and can be quantified by using figures such as 25, 80 or 160 MPa (number data-type). Since the structural design work is a quantitative calculation process, most data-types used in this ontology are number. Figure 3c displays the main data-type properties of the developed ontology.

Step 7. Define SWRL rules

Since the ontology only provides the structure and relations among different parts, an SWRL rule extending the ontology's flexibility is there to meet the structural calculations' requirements. SWRL is the reasoning function in the ontology in question, creating an interoperability –between rules and ontology (both semantic and inferential). In a typical case, the SWRL rules will comprise atoms connected by the connection symbol " ^ ". There are four types of atoms used in this ontology:

- Class atoms;
- Individual Property atoms;
- Data Valued Property atoms;
- Built-in atoms.

The implication symbol "→" connects antecedent and consequence in SWRL, while the question mark "?" represents the variables in each atom. A named class and a variable can represent the class atom in the ontology, so that – for example – (?B) would express the OWL element "Beam" class in the class atom, while (?Con) would be the "Concrete" class in the OWL. An IndividualProperty atom consists in the OWL ontology of an object property together with two variables, each representing an individual in the ontology. As an example, "hasConcrete" forms an object property for the beam and can be shown in full as hasconcrete(?B,?Con). Data valued property atoms comprise the data property and two variables, of which the first represents an OWL individual and the second is either a value or a data property. Taking the volume of a beam as an example, the volume is a data valued property, which can be represented by Volume(?B,?BV). Built-in atoms can support mathematical calculations based on the structural design code. The complicated equation from structural

design code can be converted into SWRL rules. In this ontology, the built-in mathematical functions include: add, subtract, multiply, divide, sqrt and integerdivide. For example, the volume of a beam (BV) equals the cross-sectional area (Ac) multiplied by its length (L), which can be expressed by: swrlb: multiply(?BV, ?BAc, ?BL). Similarly, the volume of a structural concrete frame (STV) equals the sum of the volume of the beam, slab, column and footing, which can be expressed by: swrlb:add(?STV, ?BV, ?SV, ?CV, ?FV). A set of SWRL rules related to the structural design were extracted from Eurocode 2 and were incorporated into the development ontology for specific applications. An example rule in SWRL can be written as:

Rule example: Calculating the required reinforcement of the beam

Equation	$As = \dfrac{M}{0.9 \times h \times f_{yd}}$
SWRL:	Beam(?B)^M(?B,?BM) ^h(?B,?Bh) ^ hasReinforcement (?B,?RF)^Reinforcement(?RF)^fyd(?RF,?RFfyd)^ swrlb:multiply(?x,0.9, ?Bh, ?RFfyd) ^ swrlb:divide(?BAs, ?BM, ?x) ->As(?B,?BAs)

Step 8. Define SQWRL rules

Querying OWL ontology is done by means of Semantic Query-Enhanced Web Rule Language (SQWRL), which is a language based on SWRL. Design solutions that work can be obtained by structural engineers from SQWRLQueryTab when the design requirements are input through the Protégé query interface as SQWRL queries. Some additional examples of rules will be given in the next section's case studies. An example of demonstrating SQWRL use is:

Query example: Selecting the beam with its cross-section height less than 500mm

SQWRL	Beam(?B)^h(?B,?Bh)^ swrlb:LessThan(?Bh, 500) -> sqwrl:select(?B, ?Bh)

What the Query example shows is selection in a Query example of a beam with a cross-sectional height less than 500 mm. Selecting this beam allows the name and height to be shown, while the built-in SWRL "lessThan" and "select" achieves the functions of selection and comparison.

4. Case study validation of the developed ontology

4.1 Case study

In this section, a case study of a concrete structural frame is used to explain how the proposed method can be used by structural designers when taking multi performance criteria into account. The framed structure is a 5-story, 3780 m^2 rectangular office building with a regular column grid of 6 m $\times$ 6 m. The overall length and width of the building is 18 m (3 $\times$ 6 m) and 42 m (7 $\times$ 6 m). The layout of the building is shown in Figure 4. The objective is to compare and select the minimum embodied CO_2 and cost of the whole structural frame.
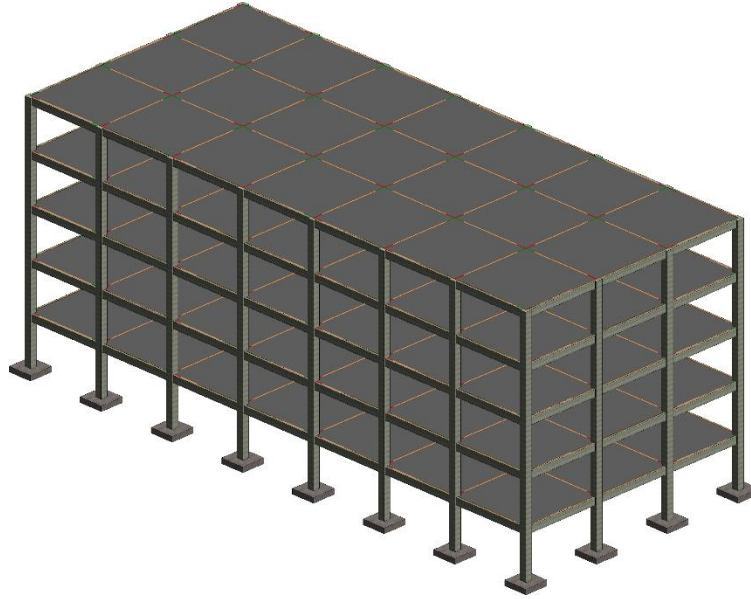
Fig.4 3D model of the structure frame in the case study

The structural frame consists of a slab, beam, column and footing. Each of these structural elements will be calculated based on the design code which has been transformed into the semantic rules in the ontology. Each concrete class (i.e., NSC, HPC and UHPC) ranging from C25 to C180, are selected to calculate the cross-sectional area and reinforcement of these structural elements (except the footing) in the system. The footing only considers the C25 concrete since there is no need to have higher compressive strength in the foundation. After calculating the required cross-sectional area and reinforcement, the volume of the concrete and the weight of the reinforcement of the structural elements is obtained, which is further converted to the CO_2 and cost by multiplying the CO_2 and cost per unit. The structural frame sums these values from each structural element and provides the total CO_2 and cost. After comparing the alternatives, the structural frame that have the least embodied carbon is recognised as the most sustainable design solution and the one with minimum cost is considered as the most cost-efficient alternatives.

Taking the slab calculation as an example, the span and load of a slab is manually input and regarded as initial facets, while the cross-sectional area, volume, reinforcement, weight, CO_2 and cost are calculated automatically based on the SWRL rules and initial facets, which are regarded as inferred facets. Similarity, the SWRL rules for beams, columns and footings' calculations are based on the basic equations in the design code. Afterwards, the total CO_2 and cost of the structural frame can be calculated by summing the values obtained from these structural elements. The SWRL rules implemented for the slab, beam, column and footing, together with the structural frame, are shown in Table 3.

Table 3a: SWRL rules for slab calculation

Rule 1	Determine the load and combination of action on the slab: $p=1.35\times Gk +1.5\times Qk$
	Slab(?S)^Gk(?S,?SGk) ^Qk(?S,?SQk)^swrlb:multiply(?x, 1.35, ?SGk) ^swrlb:multiply(?y, 1.5, ?SQk) ^swrlb:add(?Sp, ?x,?y)->p(?S? Sp)
Rule 2	Determine the design moments (M) on the slab: $M=0.125pl^2$
	Slab(?S)^p(?S,?Sp) ^length(?S,?Sl)^swrlb:multiply(?SM, 0.125, ?Sp, ?Sl,?Sl)->M(?S,?SM)
Rule 3	Determine the thickness (h) of the slab: $h=(\frac{M}{k\times b\times f_{ck}})^{0.5}$
	Slab(?S)^M(?S,?SM) ^k(?S,?Sk)^ b(?S,?Sb)^ hasConcrete(?S,?Con) ^Concrete(?Con) ^fck(?Con,?Confck)^ swrlb:multiply(?x, ?Sk, ?Sb, ?Confck) ^swrlb:divide(?y, ?SM, ?x)^swrlb:sqrt(?Sh, ?y) ->h(?S,?Sh)
Rule 4	Calculating the required reinforcement of the slab: $As=\frac{M}{0.9\times h\times f_{yd}}$

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	Slab(?S)^M(?S,?SM) ^h(?S,?Sh) ^ hasReinforcement (?S,?RF)^Reinforcement(?RF)^fyd(?RF,?RFfyd)^ swrlb:multiply(?x,0.9, ?Sh, ?RFfyd) ^ swrlb:divide(?SAs, ?SM, ?x) ->As(?S,?SAs)	
Rule 5	Calculating the volume of the slab: Volume=Ac×h	
	Slab(?S) ^ Ac(?S,?SAc) ^ h(?S,?Sh) ^ swrlb:multiply(?SV, ?Sac, ?Sh) -> Volume (?S,?SV)	
Rule 6	Calculating the weight of the slab: Weight=Volume×Density	
	Slab(?S) ^ Volume((?S,?SV) ^ hasConcrete(?S,?Con) ^Concrete(?Con) ^ Density(?Con,?ConD) ^ swrlb:multiply(?SW, ?SV, ?ConD) -> weight (?S,?SW)	
Rule 7	Calculating the weight of reinforcement of the slab: $Weight=\frac{D}{2}\times\frac{D}{2}\times 3.14 \times Length \times 78.5 \times Nbar$	
	Slab(?S) Nbar(?S,?SNbar) ^ hasReinforcement(?S,?RF)^Reinforcement(?RF) ^Diameter(?RF,?RFD) ^ SLength(?RF,?RFSL) ^ swrlb:multiply(?SRFW, 0.25, ?RFD, ?RFD,3.14, ?RFL,78.5, ?SNbar)-> Weight(?S,?SRFW)	
Rule 8	Calculating the total CO_2 of the slab: Slab CO2= Volume of slab×CO2 per unit+ Weight of reinforcement×CO2 per unit	
	Slab(?S) ^ Volume (?S,?SV) ^ hasConcrete(?S,?Con) ^Concrete(?Con) ^ SCO2(?Con,?ConCO2) ^ Weight(?S,? SRFW) ^ hasReinforcement(?S,?RF)^Reinforcement(?RF) ^RF CO2(?RF,?RFCO2) ^ swrlb:multiply(?x, ?SV, ?ConCO2) ^ swrlb:multiply(?y, ? SRFW, ? RFCO2) ^swrlb:add(?SCO2, ?x,?y)->SlabCO2(?S?,SCO2)	
Rule 9	Calculating the total cost of the slab: Weight=Volume×Density	
	Slab(?S) ^ Volume (?S,?SV) ^ hasConcrete(?S,?Con) ^Concrete(?Con) ^ UnitCost(?Con,?ConUC) ^ Weight(?S,? SRFW) ^ hasReinforcement(?S,?RF)^Reinforcement(?RF) ^ UnitCost(?RF,?RFUC) swrlb:multiply(?x, ?SV, ?ConUC) ^ swrlb:multiply(?y, ? SRFW, ? RFUC) ^swrlb:add(?SCost, ?x,?y)->SlabCost(?S? SCost)	

Table 3b: SWRL rules for beam calculation

Rule 1	Determine the load from slab to beam: q=1.35*[Weight of slab/(thickness of slab*length of slab)]+1.5*Qk	
	Beam(?B) ^hasSlab(?B,?S)^Slab(?S)^SlabThickness (?S,?Sh)^SlabLength(?S,?SL)^ SlabWeight (?S,?SW) ^Qk(?S,?SQk)^swrlb:multiply(?x,0.74,?Sh, ?SL) ^ swrlb:divide(?y, ?SW,?x) ^swrlb:multiply(?z, 1.5,?SQk) ^swrlb:add(?Bq,?y,?z) ->q(?B,?Bq)	
Rule 2	Determine the design moments (M) on the beam: $M=0.125qL^2$	
	Beam(?B)^q(?B,?Bq) ^Length(?B,?BL)^swrlb:multiply(?BM, 0.125, ?Bq, ?BL,?BL)->M(?B,?BM)	
Rule 3	Determine the height of the beam: $h=(\frac{M}{k\times b\times f_{ck}})^{0.5}$	
	Beam(?B) ^M(?B,?BM) ^k(?B,?Bk)^ b(?B,?Bb)^ hasConcrete(?B,?Con) Concrete(?Con) ^ fck(?Con,?Confck)^ swrlb:multiply(?x, ?Bk, ?Bb, ?Confck) ^swrlb:divide(?y, ?BM, ?x)^swrlb:sqrt(?Bh, ?y) ->h(?B,?Bh)	
Rule 4	Calculating the required reinforcement of the beam: $As=\frac{M}{0.9\times h\times f_{yd}}$	
	Beam(?B)^M(?B,?BM) ^h(?B,?Bh) ^ hasReinforcement (?B,?RF)^Reinforcement(?RF)^fyd(?RF,?RFfyd)^ swrlb:multiply(?x,0.9, ?Bh, ?RFfyd) ^ swrlb:divide(?BAs, ?BM, ?x) ->As(?B,?BAs)	
Rule 5	Calculating the volume of the beam: Volume=b×h×Length	
	Beam(?B) ^ b(?B,?Bb) ^ h(?B,?Bh) ^ Length(?B,?Bl) ^ swrlb:multiply(?BV, ?Bb, ?Bh, ?Bl) -> Volume (?B,?BV)	
Rule 6	Calculating the weight of the beam: Weight=Volume×Density	
	Beam(?B) ^ Volume((?B,?BV) ^ hasConcrete(?B,?Con) ^Concrete(?Con) ^ Density(?Con,?ConD) ^ swrlb:multiply(?BW, ?BV, ?ConD) -> weight (?B,?BW)	
Rule 7	Calculating the weight of reinforcement of the beam: Weight=D/2×D/2×3.14×Length×78.5×Nbar	
	Beam(?B) ^Nbar(?B,?BNbar) ^ hasReinforcement(?B,?RF)^Reinforcement(?RF) ^Diameter(?RF,?RFD) ^ BLength(?RF,?RFBL) ^ swrlb:multiply(?BRFW, 0.25, ?RFD, ?RFD,3.14, ?RFL,78.5, ?BNbar)-> Weight(?B,? BRFW)	
Rule 8	Calculating the total CO_2 of the beam: Beam CO2= Volume of beam×kg CO2 per unit+ Weight of reinforcement×kg CO2 per unit	
	Beam(?B) ^ Volume (?B,?BV) ^ hasConcrete(?B,?Con) ^Concrete(?Con) ^ BCO2(?Con,?ConCO2) ^ Weight(?B,? BRFW) ^ hasReinforcement(?B,?RF)^Reinforcement(?RF) ^RFCO2(?RF,?RFCO2) ^ swrlb:multiply(?x, ?BV, ?ConCO2) ^ swrlb:multiply(?y, ? BRFW, ? RFCO2) ^swrlb:add(?BCO2, ?x,?y)->BeamCO2(?B,?BCO2)	
Rule 9	Calculating the total cost of the beam: Beam Cost= Volume of beam×Cost per unit+ Weight of reinforcement×Cost per unit	
	Beam(?B) ^ Volume (?B,?BV) ^ hasConcrete(?B,?Con) ^Concrete(?Con) ^ UnitCost(?Con,?ConUC) ^ Weight(?B,? BRFW) ^ hasReinforcement(?B,?RF)^Reinforcement(?RF) ^ UnitCost(?RF,?RFUC) swrlb:multiply(?x, ?BV, ?ConUC) ^ swrlb:multiply(?y, ? BRFW, ? RFUC) ^swrlb:add(?BCost, ?x,?y)->BeamCost(?B? BCost)	

Table 3c: SWRL rules for column calculation

Rule 1	Determine the load from slab and beam to column: N=1.35*(Weight of slab+ Weight of beam) +1.5*Qk

	Column(?C) ^hasSlab(?C,?S)^Slab(?S) ^ SlabWeight (?S,?SW)^hasbeam(?C,?B)^Beam(?B) ^ BeamWeight (?B,?BW) ^Qk(?S,?SQk)^ swrlb:add(?x, ?SW, ?BW) ^ swrlb:multiply(?y,1.35,?x) ^ swrlb:multiply(?z,1.5,?x)^swrlb:add(?CN,?y,?z)->N(?C,?CN)
Rule 2	Determine the area of the cross-section of column: Ac=(N-0.87Asfyk)/0.567fck
	Column(?C) ^ N (?C,?CN) ^ As (?C,?CAs) ^hasConcrete(?C,?Con) ^Concrete(?Con) ^ fck(?Con,?Confck) ^ hasReinforcement (?C,?RF)^Reinforcement(?RF)^fyk(?RF,?RFfyk) ^ swrlb:multiply(?x, 0.87,?CAs, ?RFfyk) ^ swrlb:subtract(?y, ?CN, ?x) ^ swrlb:multiply(?z,0.567, ?Confck) ^ swrlb:divide(?CAc, ?y, ?z) ->Ac(?C,?CAc)
Rule 3	Calculating the volume of the column: Volume= Ac×Height
	Column(?C) ^ Ac(?C,?CAc) ^ Height (?C,?CH) ^swrlb:multiply(?CV, CAc, ?CH) -> Volume (?C,?CV)
Rule 4	Calculating the weight of the column: Weight=Volume×Density
	Column(?C) ^ Volume((?C,?CV) ^ hasConcrete(?C,?Con) ^Concrete(?Con) ^ Density(?Con,?ConD) ^ swrlb:multiply(?CW, ?CV, ?ConD) -> weight (?C,?CW)
Rule 5	Calculating the weight of reinforcement of the column: Weight=D/2×D/2×3.14×Length×78.5×Nbar
	Column(?C) ^Nbar(?C,?CNbar) ^ hasReinforcement(?C,?RF)^Reinforcement(?RF) ^Diameter(?RF,?RFD) ^ CLength(?RF,?RFCL) ^ swrlb:multiply(?CRFW, 0.25, ?RFD, ?RFD,3.14, ?RFCL,78.5, ?CNbar)-> Weight(?C,? CRFW)
Rule 6	Calculating the total CO_2 of the column: Column CO_2= Volume of column×kg CO_2 per unit+ Weight of reinforcement×kg CO_2 per unit
	Column(?C) ^ Volume (?C,?CV) ^ hasConcrete(?C,?Con) ^Concrete(?Con) ^ CCO2(?Con,?ConCO2) ^ Weight(?C,? CRFW) ^ hasReinforcement(?C,?RF)^Reinforcement(?RF) ^RFCO2(?RF,?RFCO2) ^ swrlb:multiply(?x, ?CV, ?ConCO2) ^ swrlb:multiply(?y, ? CRFW, ? RFCO2) ^swrlb:add(?CCO2, ?x,?y)->ColumnCO2(?C,?CCO2)
Rule 7	Calculating the total cost of the column: Column Cost= Volume of column×Cost per unit+ Weight of reinforcement×Cost per unit
	Column(?C) ^ Volume (?C,?CV) ^ hasConcrete(?C,?Con) ^Concrete(?Con) ^ UnitCost(?Con,?ConUC) ^ Weight(?C,? CRFW) ^ hasReinforcement(?C,?RF)^Reinforcement(?RF) ^ UnitCost(?RF,?RFUC) swrlb:multiply(?x, ?BV, ?ConUC) ^ swrlb:multiply(?y, ? CRFW, ? RFUC) ^swrlb:add(?CCost, ?x,?y)->ColumnCost(?C? CCost)

Table 3d: SWRL rules for footing calculation

Rule 1	Determine the total weight of building per rooting: Fk= weight of Slab(SW)+ weight of beam(BW)+ weight of column(CW)
	Footing(?F) ^hasSlab(?F,?S)^Slab(?S)^SW(?S,?SW)^ ^hasBeam(?F,?B)^Beam(?B)^BW(?B,?BW) ^hasColumn(?F,?C)^Column(?C)^CW(?C,?CW) ^swrlb:add(?FFk, ?SW, ?BW,)->Fk(?F,?FFk)
Rule 2	Determine the area of the footing: Area=$\frac{F_k}{P_{gk}}$
	Footing(?F)^ Pgk(?F,?FPgk)^Fk(?F,?FFk)^ swrlb:divide(?FArea, ?FFk, ?FPgk) ->Area(?F,?FArea)
Rule 3	Calculating the volume of the footing: Volume= Area×Height
	Footing(?F) ^ Area(?F,?FArea) ^ Height(?F,?FH) ^ swrlb:multiply(?FV, ?FArea, ?FH) ->(?F,?FV)
Rule 4	Calculating the weight of the footing: Weight=Volume×Density
	Footing(?F) ^ Volume((?F,?FV) ^ hasConcrete(?C,?Con) ^Concrete(?Con) ^ Density(?Con,?ConD) ^ swrlb:multiply(?FW, ?FV, ?ConD) ->Weight (?F,?FW)
Rule 5	Calculating the weight of reinforcement of the footing: Weight=D/2×D/2×3.14×Length×78.5×Nbar
	Footing(?F) ^Nbar(?F,?FNbar) ^ hasReinforcement(?F,?RF)^Reinforcement(?RF) ^Diameter(?RF,?RFD) ^ FLength(?RF,?RFFL) ^ swrlb:multiply(?FRFW, 0.25, ?RFD, ?RFD,3.14, ?RFFL,78.5, ?FNbar)-> Weight(?F,? FRFW)
Rule 6	Calculating the total CO_2 of the footing: Footing CO_2= Volume of footing×kg CO_2 per unit+ Weight of reinforcement×kg CO_2 per unit
	Footing(?F) ^ Volume (?F,?FV) ^ hasConcrete(?C,?Con) ^Concrete(?Con) ^ FCO2(?Con,?ConCO2) ^ Weight(?F,? FRFW) ^ hasReinforcement(?F,?RF)^Reinforcement(?RF) ^RFCO2(?RF,?RFCO2) ^ swrlb:multiply(?x, ?FV, ?ConCO2) ^ swrlb:multiply(?y, ? FRFW, ?RFCO2) ^swrlb:add(?FCO2, ?x,?y)->FootingCO2(?F,?FCO2)
Rule 7	Calculating the total cost of the footing: Footing Cost= Volume of footing×Cost per unit+ Weight of reinforcement×Cost per unit
	Footing(?F) ^ Volume (?F,?FV) ^ hasConcrete(?F,?Con) ^Concrete(?Con) ^ UnitCost(?Con,?ConUC) ^ Weight(?F,? FRFW) ^ hasReinforcement(?F,?RF)^Reinforcement(?RF) ^ UnitCost(?RF,?RFUC) swrlb:multiply(?x, ?SV, ?ConUC) ^ swrlb:multiply(?y, ? FRFW, ? RFUC) ^swrlb:add(?FCost, ?x,?y)->FootingCost(?F? FCost)

Table 3e: SWRL rules for structure frame calculation

Rule 1	Determine the total volume of structural frame: Volume of structural frame= Volume of Slab*number+ Volume of beam*number + Volume of column*number + Volume of footing*number
	Structure(?ST) ^hasSlab(?ST,?S)^Slab(?S)^Slab Volume (?S,?SV)^ ^hasBeam(?ST,?B)^Beam(?B)^BeamVolume (?B,?BV) ^hasColumn(?ST,?C)^Column(?C)^ColumnVolume (?C,?CV) ^hasFooting(?ST,?F) ^Footing(?F)^FootingVolume (?F,?FV) ^swrlb:add(?STV, ?SV, ?BV,CV,FV) ->StructureVolume (?ST,?STV)

	Determine the total CO2 of structural frame: CO2 of structural frame= CO2 of Slab*number + CO2 of beam*number + CO2 of column*number + CO2 of footing*number
Rule 2	Structure(?ST)^ hasSlab(?ST,?S)^Slab(?S)^SlabCO2 (?S,?SCO2)^ ^hasBeam(?ST,?B)^Beam(?B)^BeamCO2(?B,?BCO2) ^hasColumn(?ST,?C)^Column(?C)^ColumnCO2 (?C,?CCO2) ^hasFooting(?ST,?F) ^Footing(?F)^FootingCO2(?F,?FCO2) ^swrlb:add(?ST CO2, ?SCO2, ?BCO2,CCO2,?FCO2) ->StructureCO2 (?ST,?STCO2)
	Determine the total cost of structural frame: Cost of structural frame= Cost of Slab*number + Cost of beam*number + Cost of column*number + Cost of footing*number
Rule 3	Structure(?ST)^ hasSlab(?ST,?S)^Slab(?S)^SlabCost (?S,?SCost)^ ^hasBeam(?ST,?B)^Beam(?B)^BeamCost (?B,?BCost) ^hasColumn(?ST,?C)^Column(?C)^ColumnCost (?C,?CCost) ^hasFooting(?ST,?F) ^Footing(?F)^FootingCost (?F,?FCost) ^swrlb:add(?ST Cost, ?SCost, ?BCost,CCost,?FCost) ->StructureCost (?ST,?STCost)

After the implementation of the SWRL rules, the SQWRLquery is used to obtain feasible design solutions from SQWRLQueryTab. For example, to display the total CO_2 and cost of structural frame, the following SQWRL can be used:

SQWRL1-1: Display total CO_2 and cost of structural frame

SQWRL	StructureFrame(?SF) ^TotalVolume(?SF,?SFV) ^TotalCost(?SF,?SFC) ^TotalCO2(?SF,?SFCO)-> sqwrl:select(?SF, ?SFV, ?SFC, ?SFCO)

Figure 5 demonstrates the execution and results of SQWRL1-1 in SQWRLQueryTab. By executing the SQWRL Query 1-1, 36 types of structural frames are shown with the different value of the volume, embodied CO2 and cost (Fig.5). The structural engineer can make choices depending on these results. For example, if the structure engineer aims to choose the structure frame with the lowest embodied carbon, then the structure made of C160 meets the requirement; if the structure engineer aims to choose the structure frame with the lowest cost, then the structure made of C45 meets the requirement; Although the there is a "trade-off" between a lower embodied carbon and a minimum cost, it gives the structure engineer an quantitative understanding of the environmental and cost performance of a structure between the different choice. From the comparison, it is obvious which structural frame has the minimum embodied carbon and which one has the minimum cost, although they belong to different structural frames. For a more in-depth comparison, the outputs from the ontology were switched to Excel and schematically shown in Figures 6 and 7.

Fig.5 Execution and results of Query 3-1 for structural frame selection
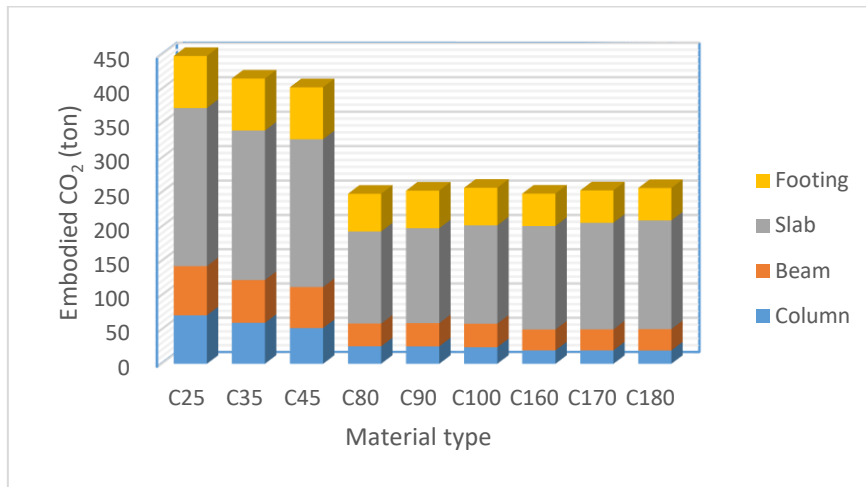

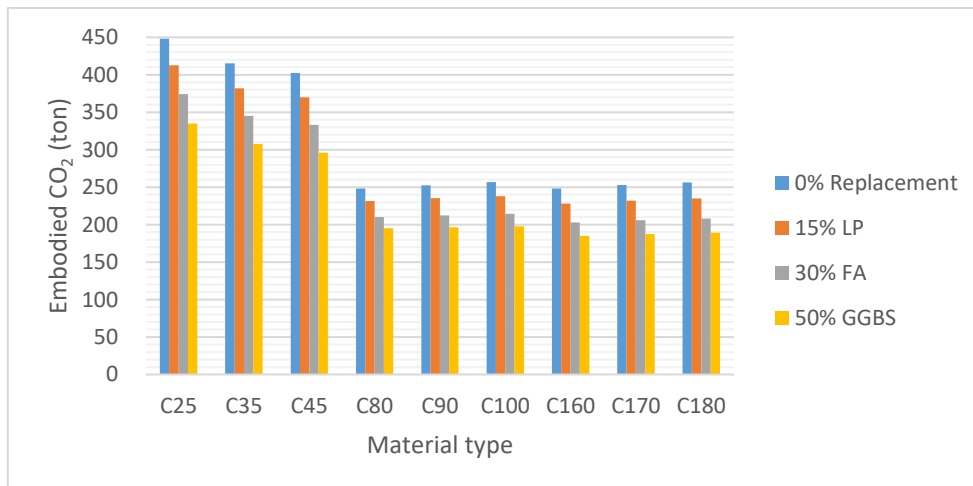Fig.6 (a) Composition of embodied CO_2 for a structural frame

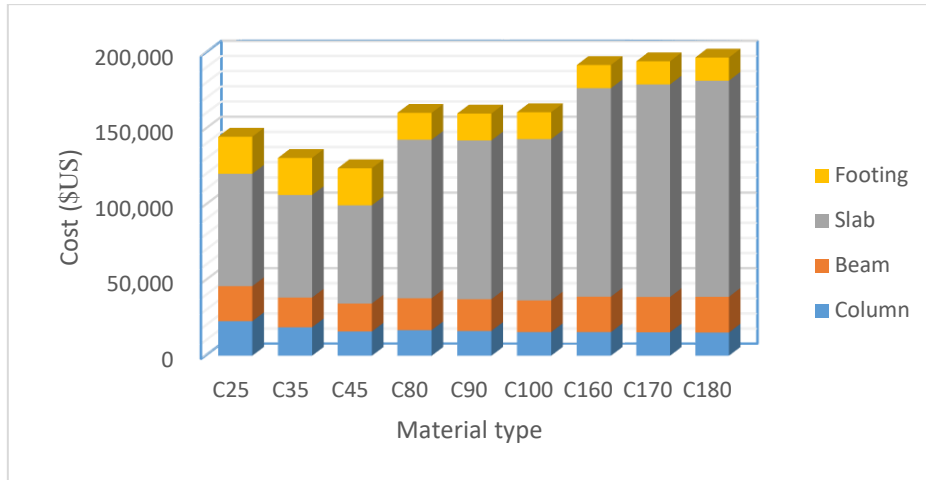Fig.6 (b) Composition of embodied CO_2 for a structural frame with SCMs

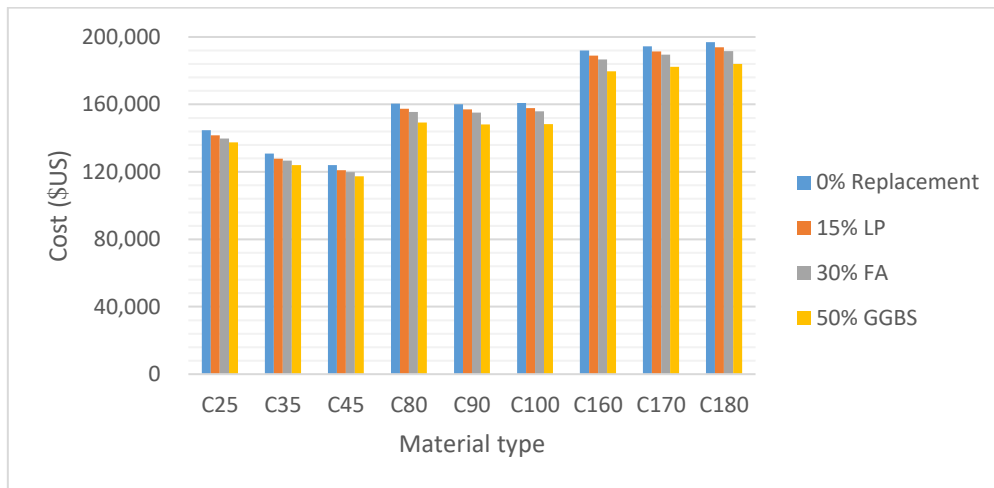Fig.7(a) Composition of cost for a structural frame

Fig.7(b) Composition of cost for a structural frame with SCMs

4.2 Discussion

From the results, it is easy for a structural engineer to make decisions since the results provide information regarding the environmental impact and cost of the whole structure, and give a quantitative comparison between different choices. From Figure 6, 36 design alternative solutions ranging from NSC to UHPC show the total embodied CO_2 of a structural frame, which all satisfy the requirements of the structural design code. It is obvious that the structural frame made of NSC has the highest embodied CO_2, while that of HPC and UHPC have similar values, which is roughly 60% of that for NSC. From a structural element level, the slab plays an important role, more than the other elements, accounting for over 50% of the total CO_2 of a structure due to a large amount of concrete used in slab. Furthermore, the CO_2 footprint is reduced consistently using SCMs compared to no-SCMs for all types of concrete. This reduction is especially evident when using 50% GGBS, which obtained the lowest CO_2 in all concrete types, compared to that of using 30% FA and 15% LP. From Figure 7, UHPC has the highest cost, followed by HPC and NSC. However, the structure made of C45 costs less compared to C25. It also can be concluded that the concrete with the lowest strength did not

necessarily mean that it would lead to a cost reduction. Furthermore, it is noted that the structural frame made of UHPC costs approximately 1.5 times more than that for NSC from a material perspective. Similar to the CO_2 results, the slab also account for over 50% of the total cost of a structure. This means that reducing the concrete volume of a slab is an effective way to cut down both cost and the CO_2 footprint of a structure. Despite some interesting findings, there still exist some limitations in this work, as follows:

(1) In terms of cost of the whole structure, this paper only considers the material level cost. In practice, however, the influence of on-site construction (i.e., concrete formwork, labour and equipment for fabrication or erection, construction schedule, etc.) needs to be considered. For example, the cost of a structural frame using UHPC is approximately 1.5 times greater than that of the structural frame used for NSC in this study. The benefit of using HPC or UHPC includes reduced formwork, labour and equipment, and the increased overall net area is not included due to the limited reference and difficulties to quantify it.

(2) The structural design methods for UHPC follows that of NSC (formulas) and some reference papers because there is no commonly accepted design code and constitutive relationship regarding this aspect. It is more convincing to employ commonly accepted design equations for UHPC in future work.

(3) The built-in mathematical functions of SWRL in the ontology only offers a small set of basic computational operations. Some of the complex structural design formulas were first converted into simple formulas and then into the SWRL rule format, which can be improved by developing more built-in functions of SWRL to fulfil the structural design.

(4) There still exists a small number of parameters which need to be manually populated in the ontology, which means it is still not fully automated in the whole design process. It is expected that interaction between the developed ontology and building information modeling can enhance the ability of automatization.

(5) The prototype system is limited in the Protégé software environment. It is still challenging for structural engineers with little knowledge about ontology engineering to use SWRLTab for defining structural design principles and query the knowledgebase. It is expected to explore more user-friendly tools to assist structural design with combined consideration of environmental impact and cost.

This research intends to investigate a novel approach to model several related human knowledge and integrate them together to form up a base for holistic decision making to allow structural engineer to contribute largely to sustainable building design. The focus lies on the knowledge modelling using ontology, including taxonomy development, reasoning rules (using SWRL), and inter-relationship among several related domain knowledge. These knowledge are domain oriented, and need to be modelled by domain engineer, in this case structural engineer, supported with necessary computing background; in its full maturity, a software tool will be developed to allow structural engineer to update and maintain these relevant knowledge base through plan language.

As an initial attempt, this paper discusses the possibility of using ontology and SWRL rules to model structural design knowledge together with sustainability and cost issues. The predefined SWRL rules act as a "structural analysis tool" to calculate load capacity of structural components and total values of volume, embodied carbon as well as cost. It demonstrates a new

way of working for structural engineer to achieve sustainable design in a holistic way. The result presented in this paper demonstrate a way to create such a knowledge base; and the structural engineer can query this to get different design alternatives fulling different requirements.

In the next stage, the knowledge base is planned to be developed as the backbone knowledge services supported by BIM with an open and standardized interface, therefore all those related software, e.g. structural design / analysis, costing, and sustainability analysis etc. can be linked to form up an integrated process.

5. Conclusion

This paper develops a novel and feasible approach for structural engineer to achieve more comprehensive structural designs, where sustainability criteria, e.g. low carbon and CO_2 emission, life cycle costing along with structural safety are holistically considered through reasoning based knowledge processing. A comprehensive knowledge base for multi-perspective structural design across different sectors is developed, which includes relevant taxonomy, ontology, and SWRL rules. The knowledge base has been validated and a full building case study was used to demonstrate its practical use; where NSC, HPC and UHPC different type of materials with and without SCMs are used as comparison and alternatives. The approach combines sustainability and cost with safety knowledge; provides multi-perspectives solutions considering safety, low carbon and cost; it demonstrates a new way of working for structural engineer to achieve ultimate sustainable design with the help of intelligent knowledge base.

Within the case study, the NSC, HPC and UHPC with and without SCMs, whose concrete classes range from C25 to C180, are selected as fundamental data to calculate the CO_2 and cost of a whole structure. The embodied impact and cost of a structure frame is mainly concentrated in the slab as the volume of the slab is large, regardless of concrete type. Regarding the environmental impact, the structural frame made of UHPC with 50% GGBS added has the least embodied CO_2 compared to that of NSC and HPC with 50% GGBS. Regarding cost, the structural frame made of NSC with 50% GGBS shows the minimum cost compared to that of HPC and UHPC. Using the proposed approach, a structural engineer can focus on the important part that most influences CO_2 and cost, and can postpone less urgent decisions to the later design stage.

While the purpose of the approach based on developed ontology is to improve the decision-making process for, in this case, a structure with a concrete frame, the model can be extended to other frame materials including timber and steel. Meanwhile, the method can be further expanded for the use of institutional learning, to conclude from the former design experiences to guide better future designs. It should be mentioned that the developed approach is focused on the environmental impact and cost the of structural frame which is based on the structural components. It is expected that non-structural components in which the mechanical system, electrical system, plumbing system and architectural features can be included from a whole building perspective in the future work. In addition, in terms of cost of a structural frame, the influence of on-site construction (i.e., concrete formwork, labour and equipment for fabrication or erection, construction schedule, etc.) needs to be considered in the future work. Lastly, the case study used in this work is a simple layout of a structural frame with a regular column grid. More complicated case applications will be required to validate the applicability and serviceability of the proposed structural design ontology.

Acknowledgements

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