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Research paper

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.

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

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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 labour 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 optimized 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