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The influence of life cycle inventory approaches on the choice of structural systems to reduce the embodied greenhouse gas emissions of tall buildings

J Helal[1], A Stephan[2] and R H Crawford[3]

[1] Lecturer in Construction Management, University of Melbourne, Australia
[2] Professor of Construction Technology and Environmental Assessment, Université Catholique de Louvain, Belgium
[3] Associate Professor in Construction, University of Melbourne, Australia

Email: james.helal@unimelb.edu.au

Abstract. The construction of tall buildings generates a high spatial and temporal concentration of greenhouse gas (GHG) emissions. Research has shown that as building height increases, more resources per floor area are required to withstand the increasing effects of wind and earthquake loads. This has major implications for the environmental performance of tall buildings since the embodied GHG emissions (EGHGE) of structural systems tend to represent the greatest portion of the life cycle GHG emissions of tall buildings. In mitigating the effects of climate change, life cycle assessment (LCA) has been proposed as an early stage design tool to facilitate the choice of structural systems for tall buildings. However, international standards on LCA do not specify which of the three main life cycle inventory (LCI) approaches to use - process analysis, environmentally-extended input-output analysis or hybrid analysis. The aim of this paper is to evaluate the influence of LCI approaches on the choice of structural systems for tall buildings to minimise their embodied GHG emissions.

The effects of LCI approaches on the choice of structural systems for tall buildings are evaluated using 10 tall buildings, ranging in height from 10 to 50 storeys, parametrically designed using finite element modelling. Two alternative structural systems are proposed and various LCI approaches are used to compare their EGHGE. The paper demonstrates that varying the LCI approach can significantly influence the values of EGHGE of structural systems for tall buildings by up to 116%. Notably, the paper demonstrates that, in minimising EGHGE, the adopted LCI approach can influence the choice of structural systems for tall buildings. The findings of this study confirm the need for clarity, transparency and comprehensiveness in the use of LCI approaches for comparative LCA studies, particularly in the structural design of tall buildings.

1. Introduction

In its recent landmark special report titled ‘Global Warming of 1.5°C’, the Intergovernmental Panel on Climate Change (IPCC) [1] declared that drastic changes are required by governments, industries and societies to limit global warming to 1.5°C above pre-industrial levels. To meet this target, global anthropogenic greenhouse gas (GHG) emissions, the most significant driver of climate change, must be reduced by at least 49% of 2017 levels, by 2030 [1]. Rapid and far-reaching transitions in the building industry, which is responsible for 39% of global anthropogenic GHG emissions [2], are required to mitigate the effects of climate change.

Regulations and current attempts to improve the environmental performance of buildings have principally focused on operational environmental flows, which are resources related to operational activities such as heating, cooling and lighting. However, studies have revealed that embodied environmental flows in buildings, which are resources related to construction and material production activities, are often underestimated [3]. The World Green Building Council [2], in its recently published report titled 'Bringing Embodied Carbon Upfront', estimates that embodied GHG emissions (EGHGE) will be responsible for half of the entire GHG footprint of new construction between now and 2050. EGHGE is particularly significant in tall buildings, due to high material requirements.

The increasing rate of urbanisation has seen an accelerated trend in the construction of tall buildings. From 2000 to 2018, the total number of buildings taller than 200 m increased by 460%, from 263 to 1,478 [4], globally. The number of tall buildings is expected to continue to grow as a solution to the challenges of urbanisation and as a means of establishing more compact cities that are attributed with less car dependency, better public transport services and better health outcomes [5]. To minimise the EGHGE of tall buildings, several studies have used a comparative life cycle assessment (LCA) approach to examine equivalent structural systems for tall buildings [6-10]. Their results demonstrate the importance of the choice of structural system in the reduction of embodied environmental flows. However, international standards on LCA do not specify which of the three main life cycle inventory (LCI) approaches to use - process analysis, environmentally-extended input-output analysis or hybrid analysis (see Section 2 for details). As a result, these studies have used readily available databases, which rely on LCI approaches that have been shown to suffer from systemic incompleteness [11-14]. Consequently, the approaches adopted by these studies do not yield reliable findings that can help accurately guide the structural design of tall buildings to minimise embodied environmental flows.

In creating sustainable cities and communities, consistent with Goal 11 of the Sustainable Development Goals, there is a need to develop structural design frameworks for tall buildings that consider EGHGE upfront. In line with the 'Reduce' and 'Optimise' principles set out by the World Green Building Council [2], these frameworks ought to apply design approaches that minimise the quantity of construction materials required and their associated EGHGE.

1.1. Aim and scope

The aim of this study is to demonstrate the influence of life cycle inventory (LCI) approaches on the embodied greenhouse gas emissions (EGHGE) of structural systems for tall buildings.

Due to the relative complexity and cost of life cycle assessment (LCA) studies, simplified LCA methodologies are often used to assess the environmental flows of tall buildings. The most common and widespread simplification in the LCA of tall buildings is to evaluate GHG emissions as the sole flow. Such an approach is referred to as a life cycle GHG emissions assessment. By adopting this approach, this paper circumvents the relative complexity of a comprehensive LCA while still aiding decision-making in buildings [15, 16].

Structural systems are designed to perform their intended function throughout their design working life, with minimum maintenance and no structural repair being necessary [17]. Consequently, the recurring EGHGE of structural systems are considered negligible. Additionally, the GHG emissions involved in the end-of-life stage of buildings are not considered due to this stage typically representing less than 1% of the total energy requirement [18] and due to the large uncertainties regarding the demolition and deconstruction processes decades into the future. As such, this paper focuses on the initial EGHGE of structural systems, which have been shown to represent the greatest portion of the life cycle GHG emissions of tall buildings [10], even when underestimated due to the use of incomplete LCI approaches.

According to European Standard EN 15978:2011, the life cycle of a building, as seen in Figure 1, is divided into four stages: product stage (A1-A3), construction stage (A4-A5), use stage (B1-B7) and end-of-life stage (C1-C4) [19]. The scope of this paper, as illustrated and summarised in Figure 1, encompasses the EGHGE of structural systems for tall buildings in the product stage (A1-A3) and the construction stage (A4-A5) as influenced by different LCI approaches.

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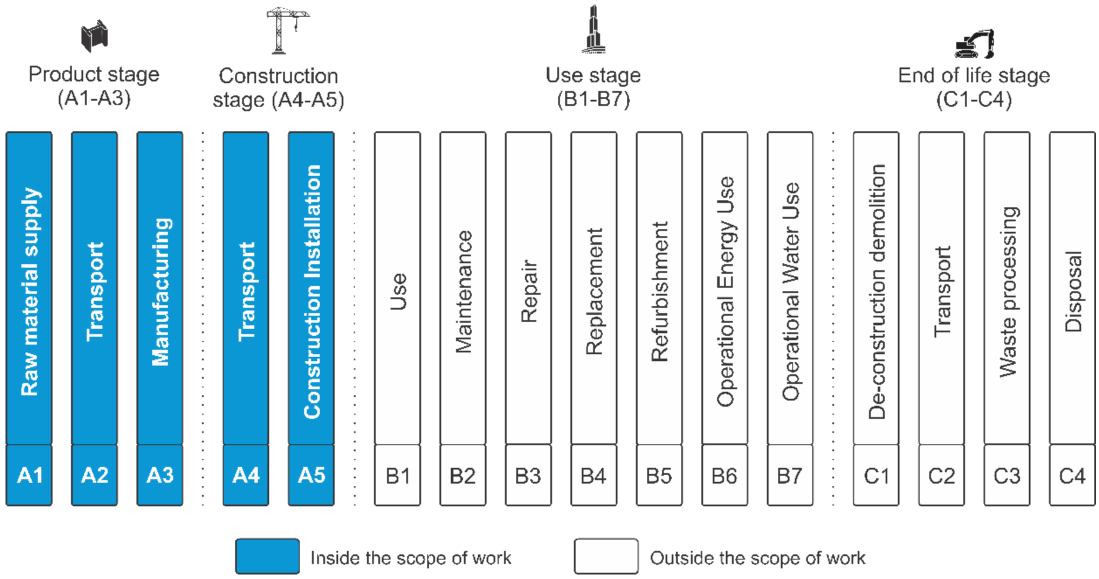

Figure 1 - Scope of the work according to EN 15978:2011

2. Types of life cycle inventory analysis approaches

Life cycle inventory (LCI) analysis consists of listing the inputs and outputs associated with a service or product and is an integral part of a life cycle assessment (LCA). There are three broad approaches for compiling an LCI:

- process analysis, which is a bottom-up approach where a product is studied according to the series of processes that represent its life cycle;
- environmentally extended input-output analysis (EEIOA), which is a top-down approach where economy-wide input-output tables are studied to quantify the material and non-material inputs and outputs required throughout the entire supply chain associated with production; and
- hybrid analysis, which combines the first two approaches by merging process data with macroeconomic data to avoid the inherent truncations in the process approach and the high levels of aggregation in the EEIOA approach.

Sections 2.1 to 2.3 discuss the different LCI approaches in more detail.

2.1. Process analysis

Process analysis relies on data specific to the considered product or service to calculate its inputs, outputs and resulting environmental effects across its life cycle [11]. The specificity of process analysis yields a high level of accuracy but the cost of this specificity is systemic incompleteness due to the difficulty of exhaustively assessing the supply chain of a product [11, 14, 20]. Due to constraints in time, budget and data availability, the following levels of truncation are inherent to a process analysis:

- upstream truncation, where higher order processes in the supply chain are neglected;
- downstream truncation, where intermediate manufacturing processes are omitted; and
- sideways truncation, where non-material processes are neglected [20].

Crawford [11] showed truncation errors can be up to 87% of the embodied energy (EE) of a building material or product, thus demonstrating that process analysis can greatly underestimate EE in buildings.

2.2. Environmentally-extended input-output analysis

By assuming that economic flows provide a fair indication of physical flows, input-output tables, which record top-down macro-economic data covering the entire economy, can be used to perform an environmentally-extended input-output analysis (EEIOA). This can be done by integrating environmental data of the correct format, such as tonnes of greenhouse gas (GHG) emissions, with

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macroeconomic consumption activity data [20, 21]. This facilitates the calculation of upstream and indirect environmental effects, which are not exhaustively captured by a process analysis.

Input-output data is typically aggregated at the industry and product group level. For example, the input-output tables of the Australian National Accounts of 2015-2016 show that $20.4b AUD of the Residential Building Construction (RBC) product group was produced by the Construction Services industry while $10.3b AUD of the same product group was produced by the Non-Residential Building Construction industry and so on, resulting in a total of $87.5b AUD of RBC products being produced by all industries [22]. Such aggregation in the assessment of a product system like residential buildings leads to a loss of useful specificity, such as the distinction between low-rise and tall residential buildings, making it difficult to assess specific products and services taking place within the same sector [14, 23].

2.3. Hybrid analysis

To address the limitations inherent in both process analysis and EEIOA, various hybrid LCI approaches have been proposed to combine process and input-output data in a variety of formats. The four main hybrid LCI approaches that have been identified in the literature are Tiered, Matrix Augmentation, Integrated and Path-Exchange (PXC). These approaches are explained in detail in the review by Crawford et al. [13]. The main purpose of a hybrid-based LCI approach is to provide a more complete set of information when compiling the inventory of a product system.

3. Existing comparative life cycle assessment studies of structural systems for tall buildings

A total of five comparative life cycle assessment (LCA) studies of structural systems for tall buildings have been identified in the existing literature [6-10]. The case study tall buildings range in height from 15 to 120 storeys and are designed to be built in South Korea, Italy or China. The identified studies assess a range of structural systems for tall buildings including rigid frame, braced frame, shear wall, outrigger and belt, and diagrid. The identified studies also consider reinforced concrete, steel and composite as alternative structural materials. Figure 2 summarises the existing comparative LCA studies of structural systems for tall buildings by depicting their adopted life cycle inventory (LCI) approaches and their considered building heights, structural materials and structural systems.

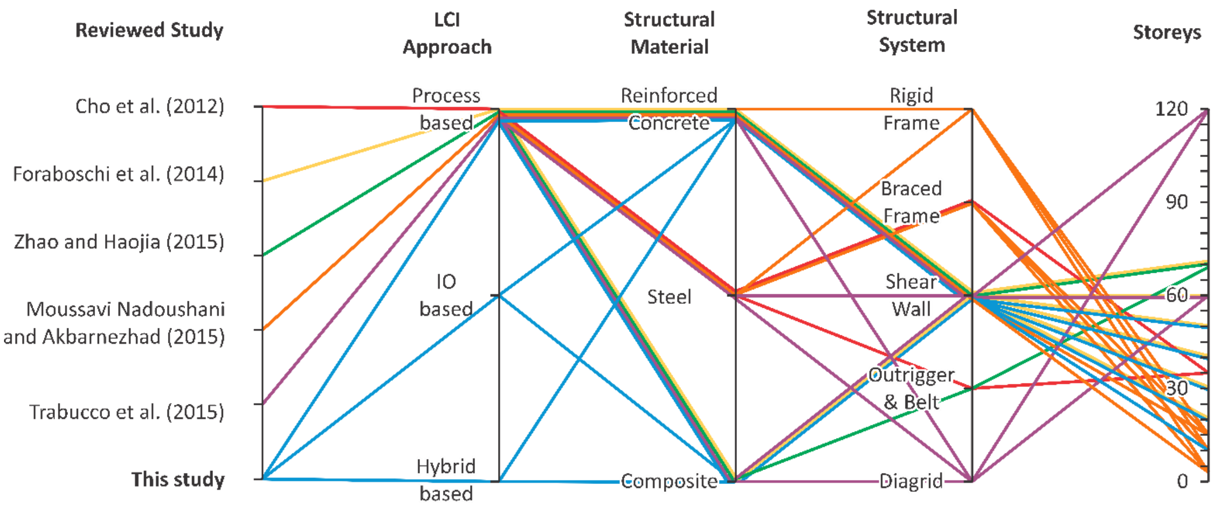

Figure 2 - Summary of existing comparative life cycle assessment studies of structural systems for tall buildings

As seen in Figure 2, existing comparative LCA studies on the structural systems of tall buildings explore various structural materials (reinforced concrete, steel and composite), structure systems (rigid frame, braced frame, outrigger and belt, shear wall and diagrid) and heights (up to 120 storeys). However, these studies systematically use a process analysis, with the most common source of environmental data being the Inventory of Carbon and Energy (ICE) [24], which has been shown to be

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systematically incomplete and inconsistent [11-14]. Additionally, these studies lack the required levels of transparency and data accessibility for their results to be comparable and reproducible and their conclusions to be validated. Consequently, these studies do not yield reliable findings that can help guide architects and engineers in selecting structural systems for tall buildings to minimise their EGHGE.

4. Method

Parametric modelling is adopted to assess the influence of life cycle inventory (LCI) approaches on the embodied greenhouse gas emissions (EGHGE) of structural materials for tall buildings. Due to the complex process of structural design for tall buildings, finite element modelling and analysis is used to ensure that structural systems meet the required performance criteria. The method of structural analysis and design is presented in Section 4.1. The material quantities, which are derived and extracted from the finite element models, are then converted to EGHGE using process-based, input-output-based, and hybrid-based LCI approaches, as presented in Section 4.2.

4.1. Structural analysis and design of tall buildings

To understand the influence of LCI methods on the EGHGE of tall buildings, 10 finite element models of tall buildings were parametrically designed having 10, 20, 30, 40 or 50 storeys. Two alternative structural systems were designed for each building height. These structural systems are: (1) a reinforced concrete (RC) shear wall and frame (RCSW+RCF) and (2) a RC shear wall and steel frame (RCSW+SF). Apart from the shear wall of the 50-storey tall buildings, which required the use of 50 MPa RC, a 32 MPa RC was used for the design of all the finite element models. A maximum yield strength of 360 MPa was used for all steel sections. The relevant Australian Standards for structural design are adopted by this study to ensure that all the constructed finite element models meet the required structural performance criteria. The commercial software ETABS [25] is used for the finite element modelling and analysis of tall buildings. Widely regarded as one of the most reliable and powerful structural analysis and design software for multi-storey buildings, ETABS has been used for the design and analysis of some of the most complex and iconic tall buildings in the world, including Burj Khalifa, the tallest building in the world as of 2020 [4].

Material properties and geometric properties related to floor plan shape (square) and width (30 m), column span (7.2 m) and inter-storey heights (3.5 m) are kept constant to isolate the influence of LCI methods on EGHGE. These building parameters and their values were selected based on best and common practices in the design and construction of tall buildings. Permanent loads, imposed loads (2 kPa), façade loads (3.5 kN/m), wind loads and earthquake loads were all considered for the structural design. The adopted building parameters and structural design loads, along with a detailed justification of their values, are presented as supplementary information at http://doi.org/10.26188/5e160f6f496e0.

4.2. Quantifying the embodied greenhouse gas emissions of structural systems for tall buildings

The EGHGE of structural systems in tall buildings are calculated using Equation 1:

$$EGHGE_{SS,LCI} = \sum_{m=1}^{M} \left(Q_{m,SS} \times EGHGEC_{m,LCI}\right) \quad \text{(Eq. 1)}$$

Where $EGHGE_{SS,LCI}$ = embodied GHG emissions of structural system *SS* in $kgCO_2$-e calculated using life cycle inventory approach *LCI* (i.e. process-based, input-output-based or hybrid-based); $Q_{m,SS}$ = quantity of material *m* in structural system *SS* (e.g. steel in kg); and $EGHGEC_{m,LCI}$ = embodied GHG emissions coefficient of material *m* (e.g. 2.90 $kgCO_2$-e/kg for hot-rolled steel) developed using life cycle inventory approach *LCI*.

Compiled by Crawford *et al.* [26], EGHGE coefficients from the Environmental Performance in Construction (EPiC) Database were used to demonstrate process, input-output and hybrid-based LCI approaches. The EPiC Database adopts the Path-Exchange (PXC) method to develop hybrid coefficients

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for various embodied environmental flows, including EGHGE. The EPiC Database and PXC method were selected for this study since PXC remains to be the most efficient LCI method while maintaining comprehensive coverage of the product system boundary. The method involves the mathematical disaggregation of an input-output table to enable the replacement of equivalent input-output pathways with specific process-based data [23]. Doing so allows this method to maintain system boundary completeness while increasing specificity. EGHGE coefficients from the Inventory of Carbon and Energy (ICE) [24], which are averaged values sourced from different Environmental Product Declarations (EPD) across various geographic regions, were used for comparative purposes since ICE is the most commonly used source of embodied energy (EE) and EGHGE for the existing studies reviewed in Section 3. All the adopted EGHGE coefficients are listed below in Table 1.

Table 1 - Embodied greenhouse gas emissions (EGHGE) coefficients used for the EGHGE of structural systems

Material	**EPiC - process coefficients** ($kgCO_2$-e/kg)	**EPiC – IO coefficients** ($kgCO_2$-e/kg)	**EPiC - hybrid coefficients** ($kgCO_2$-e/kg)	**ICE - process coefficients** ($kgCO_2$-e/kg)
RC (32 MPa)	0.168	0.068	0.170	0.126
RC (50 MPa)	0.256	0.081	0.245	0.159
Steel	2.400	1.300	2.900	1.550

Note: IO = input-output

5. Results

The material quantities of all 10 finite element models were converted to embodied GHG emissions (EGHGE) using the various coefficients listed in Table 1 and normalised per net floor area (NFA). Figure 3 presents the EGHGE/NFA of the reinforced concrete shear wall and frame (RCSW+RCF) structural system and the reinforced concrete shear wall and steel frame (RCSW+SF) structural system plotted against the number of storeys of the tall buildings using a process-based, input-output-based or hybrid-based LCI approach.

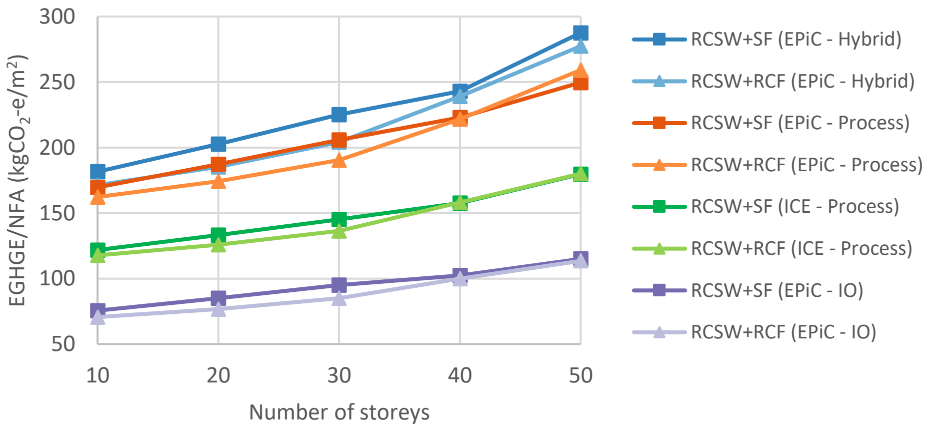

Figure 3 - Influence of life cycle inventory methods on the embodied greenhouse gas emissions per net floor area (EGHGE/NFA) of structural systems. Note: vertical axis starts at 50 $kgCO_2$*-e/m*^{2}*.*

Figure 3 reveals that varying the LCI approach can significantly influence the EGHGE/NFA of structural systems for tall buildings, by up to 116%. The results also show that when using hybrid or input-output EGHGE coefficients from the EPiC Database, RCSW+RCF had a lower EGHGE/NFA than that of RCSW+SF for all considered building heights. However, when using process coefficients from the EPiC Database, RCSW+SF achieved the lower EGHGE/NFA for the 50-storey building. Similarly, when using coefficients from the ICE database, RCSW+SF achieved the lower EGHGE/NFA for the 40 and 50 storey buildings. Further divergence in EGHGE is expected for taller buildings.

Therefore, the results indicate that the choice of LCI approach can alter the choice of structural systems for tall buildings with 40 to 50 storeys, from RCSW+RCF to RCSW+SF, to minimise EGHGE.

6. Discussion

This study has demonstrated for the first time the influence of life cycle inventory (LCI) approaches on the choice of structural systems to reduce the embodied greenhouse gas emissions (EGHGE) of tall buildings. In comparison, most existing studies conduct a comparative LCA on alternative structural systems of tall buildings using a process-based LCI approach, which has been shown to be systematically incomplete and inconsistent. By demonstrating the influence of LCI approaches on the EGHGE of structural systems, this paper establishes the need for clarity and transparency to increase the comparability between different LCA studies. This type of assessment can effectively inform future design frameworks that integrate environment assessment into the structural design of tall buildings to reduce their EGHGE.

As in any scientific inquiry, this study suffers from limitations. Firstly, this study assessed the influence of LCI approaches on tall buildings with reinforced concrete (RC) shear walls and RC or steel frames only. Thus, the findings of the study are restricted to these structural materials and systems. The study also neglected the influence of standardisation in construction, which often dictates the selection of section sizes, in order to assess the maximum potential savings in EGHGE when assessing alternative structural systems. Further research could investigate the influence of LCI approaches on tall buildings of different structural materials and systems.

7. Conclusion

This study assessed the influence of life cycle inventory (LCI) approaches on the embodied greenhouse gas emissions (EGHGE) of structural systems using 10 tall buildings parametrically designed using finite element modelling. The study demonstrates that varying the LCI approach can significantly influence the EGHGE of structural systems, by up to 116%, and can lead to different choices in structural systems to reduce the EGHGE of tall buildings. The findings of this study confirm the need for clarity, consistency, transparency and comprehensiveness in LCI methods when conducting comparative life cycle assessment (LCA) studies of structural systems for tall buildings. Therefore, it is crucial for researchers, architects and structural engineers to understand the influence of LCI approaches on the EGHGE of structural systems during the selection of appropriate structural systems for tall buildings. This will ultimately contribute to reducing the environmental effects of the built environment in line with Goal 11 of the Sustainable Development Goals: Sustainable cities and communities.

Data availability

The data that support the findings of this study, along with the adopted building parameters and structural design loads, are openly available at http://doi.org/10.26188/5e160f6f496e0. The finite element models that were constructed for this study are also openly available at http://doi.org/10.26188/5e160fe4c8eb8.

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