P. Rajagopalan and M.M Andamon (eds.), *Engaging Architectural Science: Meeting the Challenges of Higher Density: 52nd International Conference of the Architectural Science Association 2018*, pp.241–248. ©2018, The Architectural Science Association and RMIT University, Australia.

Beyond the 'premium-for-height' framework for designing structural systems for tall buildings: considering embodied environmental flows

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Abstract: During the 1960s, the Bangladeshi-American structural engineer and architect Fazlur Rahman Khan proposed a design framework for the structural systems of tall buildings titled 'premium-for-height.' Khan argued that the challenge of a structural engineer is to design structural systems that minimise the 'premium-for-height' of tall buildings as defined by the increase in material per gross floor area with increasing building height. This framework has had a profound influence and is commonly cited in the literature. However, in meeting the challenges of climate change and higher density, minimising the initial embodied environmental flows of tall buildings, such as greenhouse gases, must also become a priority in design frameworks. This paper discusses the limitations of the 'premium-for-height' framework and the importance of considering initial embodied environmental flows of tall buildings during their structural design. Finite element modelling and advanced structural analysis are proposed to assess the structural performance of tall buildings. The Path Exchange (PXC) hybrid life cycle inventory analysis method is proposed to analyse the initial embodied environmental flows of structural systems. This research forms the basis of a revised framework for the design of structural systems in tall buildings.

Keywords: tall buildings; structural systems; premium for height; embodied environmental flows.

1. INTRODUCTION

The influence of human activity on climate change is evident. Recent anthropogenic emissions of greenhouse gases (GHG), the most significant driver of climate change, are the highest they have ever been (IPCC, 2014). Urgent and fundamental changes are required, particularly in the design and construction of buildings, to mitigate the effects of climate change.

The building construction industry uses 40% of the materials entering the global economy and is responsible for 30% of landfill waste (Khasreen *et al.*, 2009). Anticipated trends in population growth, urbanisation and changes to household sizes, wealth and lifestyle are likely to increase the energy use and GHG emissions of buildings. Nevertheless, using existing systems and technologies, buildings offer the greatest abatement opportunities for reducing global GHG emissions in the short term (IPCC, 2014).

Resources, such as energy, water and carbon, flow throughout the life cycle of buildings and can be categorised into embodied flows and operational flows. Embodied flows are resources involved in the construction of buildings and the production of building materials across their supply chains. Initial embodied flows represent the embodied flows of the building as-built, while recurrent embodied flows represent the resources required to produce and replace building materials throughout the period of analysis. Operational flows are resources involved in the operation of buildings which include heating, cooling, ventilation, domestic hot water, lighting, appliances and cooking. Regulations and current attempts to improve the environmental performance of buildings have principally focused on operational energy (Ibn-Mohammed *et al.*, 2013). However, embodied energy can account for a significant portion (up to 60%) of the life cycle energy demand of a building (Treloar *et al.*, 2001; Stephan and Stephan, 2014; Huberman *et al.*, 2015). Additionally, improvements in the operational efficiency of buildings is often achieved using assemblies of high embodied energy such as thermal insulation and advanced façade systems (Huberman *et al.*, 2015). Therefore, as the operational energy efficiency of buildings improves and the operational GHG emissions decrease, embodied GHG emissions will progressively form a higher proportion of a building's life cycle environmental flows (Säynäjoki *et al.*, 2012).

The increasing rate of urbanisation has seen an accelerated trend in the construction of tall buildings, with the aim of increasing population density near employment opportunities. From 2000 to 2017, the total number of buildings taller than 200 m increased by 400% (from 263 to 1,319) (CTBUH, 2017). The number and heights of tall buildings are expected to continue growing as a solution to the challenges of urbanisation and as a means of establishing compact cities that are attributed with less car dependency, better public transport services and better health outcomes (Roo and Miller, 2000; Stevenson *et al.*, 2016). However, such construction generates a high spatial and temporal concentration of GHG emissions, a phenomenon described by Säynäjoki *et al.* (2012) as a 'carbon spike.' In fact, tall buildings can have up to 60% more embodied energy per gross floor area than low rise buildings (Treloar *et al.*, 2001). This increase in resource use is mainly due to the cumulative effect of lateral loads on the behaviour of tall buildings, whereby more resources per floor area are required for tall building structural systems to withstand the increasing effect of wind and earthquake loads (Khan, 1967). This has major implications for the environmental performance of tall buildings since the embodied GHG emissions of structural systems represents the greatest portion of the life cycle GHG emissions of tall buildings (Zhao and Haojia, 2015).

During the 1960s, the Bangladeshi-American structural engineer and architect Fazlur Rahman Khan (1967) proposed a design framework for the structural systems of tall buildings titled 'premium-for-height.' Khan argued that the challenge of a structural engineer is to design structural systems that minimise the 'premium-for-height' of a tall building as defined by the increase in material per gross floor area with increasing building height. However, in meeting the challenges of reducing climate change and addressing higher density, minimising the environmental effects associated with structural systems must become a design priority to achieve high environmental performance in tall buildings.

1.1 Aim and scope

The aim of this paper is to discuss the limitations of the 'premium-for-height' framework and the importance of also considering the embodied environmental flows of tall buildings, in addition to cost, during their structural design. The paper presents a revised framework to design the structural system of a tall building, given its geometric properties, based on embodied environmental flows, namely embodied energy (EE), embodied GHG (EGHG) emissions, embodied water (EW) and cost.

According to the European standard EN 15978:2011, a building's life cycle can be divided into four stages: product stage, construction stage, use stage and end-of-life stage (European Committee for Standardization, 2011). Structural systems of tall buildings are designed to perform their intended functions throughout their design working life with minimum maintenance and no structural repair being necessary. As such, the operational flows of structural systems are considered by this study to be negligible. Moreover, it has also been shown that the energy used during the demolition of buildings comprises approximately 1% of the building's total energy requirement (Ramesh *et al.*, 2010). Therefore, demolition flows are also assumed to be negligible in this study. This work focuses on the environmental flows of a tall building's structural system in the product stage and the construction stage. The focus on the embodied flows of structural systems is due to their predominant significance over operational flows and disposal flows (Zhao and Haojia, 2015).

1.2 Notions and definitions

1.2.1 Tall buildings

Among multiple possible definitions, this work adopts the definition for tall buildings proposed by Stafford Smith and Coull (1991) coupled with a minimum height criteria as set by Emporis Standards (2018) for a high-rise building. As such, this work defines a tall building as a building whose height is at least 35 metres and whose structural design is significantly influenced, because of its height, by lateral forces due to wind or earthquake actions. This adopted definition emphasises the influence of dynamic lateral loads on tall buildings while underlining the importance of considering them from the beginning of the design process.

1.2.2 Structural systems

A structural element is a physically distinguishable part of a structure such as a wall, column, beam, slab or connection. A structural system refers to an arrangement of structural elements capable of resisting loads. Tall buildings are generally composed of two structural sub-systems: a lateral load resisting system, which predominantly resists wind and earthquake loads; and a vertical load resisting system, which predominantly resists gravity loads (Ali and Moon, 2007). It is important to note that the actions of these structural sub-systems and their resistance to loading are not mutually exclusive. Due to the complex nature of structural interactions, a vertical load resisting system moderately resists lateral loads and contributes to the overall lateral stiffness of a tall building and *vice versa*. This work identifies the following twelve structural systems for tall buildings: (1) Shear Wall, (2) Braced Frame, (3) Rigid Frame, (4) Outrigger and Belt, (5) Framed Tube, (6) Braced Tube, (7) Bundled Tube, (8) Tube-in-Tube, (9) Diagrid, (10) Space Truss, (11) Super Frame and (12) Exoskeleton.

2. ‘PREMIUM-FOR-HEIGHT’ FRAMEWORK

2.1 Introduction

In the 1960s, Khan (1967) claimed that the design of tall buildings can be divided into two phases. The first phase involves designing the building for gravity loads without considering the effects of lateral loads. Therefore, the columns, beams and slabs are proportioned to carry the dead and live loads only. Since gravity loads cannot be reduced or dissipated by any structural manipulation, the first phase design sets the lower boundary of the overall proportions and total quantity of material per footprint area. As seen in Figure 1, a hypothetical glass dome can be used to illustrate the isolation of the tall building from lateral loads. All factors affecting the structural design of the tall building must be considered in the second phase, including the effects of wind loads and earthquake loads on the dynamic behaviour of tall buildings. To meet stiffness, strength and stability requirements, the structural designer may have to increase the sizes of columns or beams or both. The second phase, therefore, constitutes the upper bound of design in terms of material weight per gross floor area. Thus, the premium for height is defined as the difference in material weight per gross floor area between the boundaries of the two phases of design. As such, Khan (1967) claimed that the structural engineer’s challenge is to refine a known system or to find and develop new structural systems to reduce and, if possible, to eliminate the premium for height for any given building. The cumulative effect of lateral loads on the behaviour of tall buildings is clearly seen in Khan’s ‘premium-for-height’ framework as illustrated in Figure 1.

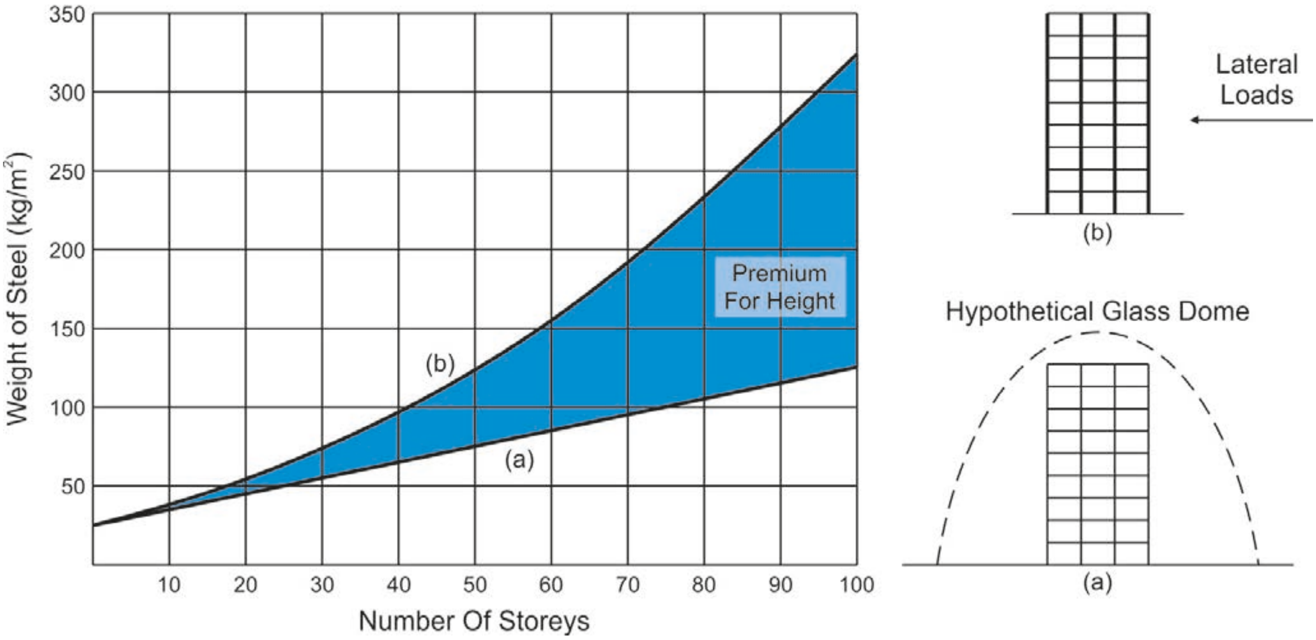

Figure 1 – ‘Premium-for-height’ framework as proposed by Khan (1967)

This framework has been used by Khan to design some of the world’s most iconic tall buildings including the John Hancock Center and Willis Tower in Chicago, Illinois. Khan’s framework has largely gone unchallenged and has remained unaltered since its introduction in the 1960s. The following section critiques the framework and highlights its limitations in selecting the structural systems and materials for tall buildings.

2.2 Limitations

In designing tall buildings, one of the most important design decisions relates to the choice of structural material. Reinforced concrete and steel remain the most commonly used structural materials for tall buildings. The choice of structural material is dictated by several considerations such as structural and non-structural design requirements, availability of materials in the local market and the experience of the local construction industry. Despite being a structural design framework, the ‘premium-for-height’ framework does not facilitate the choice of structural materials. Consider a steel structural system and a reinforced concrete structural system in a comparative study to select the preferred structural material. If the tall building is 50 storeys high, the designer might determine that the steel structural system will weigh 115 kg/m^2 of gross floor area (GFA) and the reinforced concrete structural system will weigh 775 kg/m^2 (GFA). This information alone is not sufficient to select the structural system of tall buildings since different structural materials have different effects on the construction process and the environment. As discussed in Section 1, an analysis of the environmental effects of both materials is required for the selection of structural systems while meeting the challenges of climate change and higher density. Neglecting the environmental effects of tall buildings and lacking the ability to assist in decisions related to structural materials are major limitations of the ‘premium-for-height’ framework.

The temporal patterns of GHG emissions further emphasise the need to consider the embodied GHG of tall buildings when designing their structural systems. GHG emissions released early in the life cycle of a product have a greater capacity to alter Earth's radiative balance and warm its atmosphere than later emissions (Säynäjoki *et al.*, 2012). This is due to the nature of GHG emissions in causing instantaneous and irreversible damage to the environment while lingering in the atmosphere for thousands of years (IPCC, 2014). With human activities propelling Earth towards sudden and irreversible environmental changes, designers should not wait to reduce GHG emissions in the long term, such as over the 50-year design working life of buildings. Design frameworks must consider the upfront environmental effects associated with the structural systems of tall buildings to meet short term climate change mitigation goals.

'Premium-for-height', as a measure of material per gross floor area, was considered by Khan (1967) to be a measure of cost effectiveness. In a comparison of structural systems, it is theoretically possible to have a building with a lower material per gross floor area yet have a higher cost per gross floor area due to other cost factors related to the construction process. For example, a diagrid structural system can achieve a favourable premium-for-height due to its closely spaced exterior columns and widely spaced diagonal members. However, this configuration creates an additional number of joints when compared to a framed tube, for example. The excessive number of joints increases construction cost which would not be reflected in Khan's 'premium-for-height' framework. Therefore, if cost effectiveness is to be regarded as a premium-for-height, as Khan intended it to be, a dedicated measure of total cost per gross floor area should be considered to account for all cost premiums.

Additionally, despite its significant influence on the design of tall buildings, the 'premium-for-height' framework lacks integration into software tools currently available in the industry. If presented in a user-friendly software, information graphics can have a great influence in driving design practitioners towards the optimisation of structural systems. The proposed framework, presented in Section 3 and visualised in Figure 2, incorporates data visualisation techniques to facilitate structural design decisions.

2.3 Existing studies quantifying embodied environmental flows

Studies that consider embodied environmental flows in the structural design of tall buildings are presented in this section.

Four alternative steel structural systems for a 35 storey building were studied by Cho *et al.* (2012) designed to meet an equivalent lateral deflection limit. The structural systems were evaluated according to their embodied environmental flows, which were quantified using the process analysis approach as described in Section 3.2. The use of a steel braced frame resulted in a 21% reduction in embodied energy compared to the steel rigid frame. The results clearly show the importance of structural optimisation in the reduction of embodied environmental flows.

A study by Foraboschi *et al.* (2014) assessed the embodied energy of structural systems for tall buildings composed of a reinforced concrete central core and either a reinforced concrete rigid frame or a steel rigid frame ranging in height from 20 to 70 stories. By also using a process analysis approach, the study concluded that reinforced concrete frames result in up to 44% less embodied energy per gross floor area than steel frames for buildings between 20 stories and 70 stories high.

Moncaster *et al.* (2018) explored the methodological decisions related to the structural design of tall buildings and the resultant wide variation in approach. A case study tall building was used to demonstrate the effect and importance of the following methodological variations: temporal differences in the stages considered, special differences in the material boundaries and physical disparities in the data coefficients. The study iterated the need for more clarity and transparency in calculating life cycle environmental flows to guide the structural design of tall buildings.

The following section presents a revised design framework in which the structural and environmental performances are integrated to select the structural systems for tall buildings.

3. METHOD

3.1 Establishing structural equivalency

To assess the structural performance of a proposed design, the possible structural responses are studied and divided into two domains consisting of desirable and undesirable states. The boundary between these domains is called the limit state, and entering the undesirable domain is defined as failure. A distinction is made between ultimate limit states and serviceability limit states. Ultimate limit states are states that concern the safety of people and/or the safety of the structure (Standards Australia, 2002). Failure to remain within the ultimate limit state is almost always irreversible and catastrophic, endangering lives and causing a series of financial losses. Therefore, the probability of failure to meet the ultimate limit state must be significantly reduced. Serviceability limit states are states that concern the function of the structure, the comfort of people and the appearance of the construction works (Standards Australia, 2002). The primary aim of serviceability limit states is to ensure efficient and economical in-service performance without excessive routine maintenance or down-time. The criteria for serviceability limit states are normally based on limits of deflection or vibration for normal use of the structure.

The design of tall buildings is generally governed by serviceability limit state requirements rather than by ultimate limit state requirements (Mendis *et al.*, 2007). Material requirements for reducing lateral displacements and accelerations to acceptable serviceable and comfort levels are higher than the requirements for maintaining actions and stresses below ultimate strength levels. As such, maximum deflection and acceleration at the top of a building, due to the dominance of the first mode of vibration on the overall behaviour of tall buildings, are of critical concern for the designer (Mendis *et al.*, 2007). In assessing the range of structural systems for tall buildings, structural equivalency must be established by constraining lateral displacements and accelerations to acceptable serviceability levels in response to dynamic lateral loads. Acceptable lateral displacements are adopted to limit damage to non-structural components, such as facades, partitions and interior finishes, and to limit the secondary loading effects resulting from the additional overturning moment, which is referred to as the P-Delta effect. This method will adopt a commonly used lateral displacement limit as expressed by the following equation:

$$\Delta_l = \frac{H_{\max}}{500} \tag{1}$$

where: Δ_l = Lateral displacement limit in response to a 1 in 25 year wind or earthquake event in mm; H_{max} = Maximum inter-storey drift in mm.

Acceptable accelerations are adopted to reduce the effects of motion perceptibility by users of buildings. An internationally accepted standard for motion perception in tall building design does not exist. However, research has shown that accelerations within 0.05 m/s^2 cannot be perceived by most people (Mendis *et al.*, 2007). This limit will be adopted in this framework as a response to a 1 in 25 year wind or earthquake event.

To ensure that the structural systems meet the performance criteria, the systems are modelled using a Finite Element Method (FEM) of structural analysis. The FEM procedure consists of idealising and modelling a building floor by means of discrete elements and nodes with six degrees of freedom being considered at each node. Once all the floors are modelled, a stiffness matrix and an applied load vector are generated. The system of equations thus formed for the whole structure is solved, and the displacements and accelerations at all the nodes of the system are obtained. The deflection and acceleration constraints at the top of the buildings are used to ensure that the range of structural systems under consideration are structurally equivalent according to the finite element models. Having achieved structural equivalency, the environmental effects of each structural system are assessed according to the method described in Section 3.2.

3.2 Quantifying embodied environmental flows

Life Cycle Assessment (LCA) is a compilation and evaluation of the inputs, outputs and potential environmental effects of a service or product throughout its life cycle (Crawford *et al.*, 2018). Listing the inputs and outputs associated with a service or product is referred to as a life cycle inventory (LCI). There are three broad approaches for compiling an LCI: process analysis, environmentally extended input-output analysis (EEIOA) and hybrid approaches (Crawford *et al.*, 2018). Process analysis is a bottom-up approach, where a product is studied according to the series of processes that represent its life cycle. EEIOA is a top-down approach where economy-wide input-output tables are studied to quantify the material and non-material inputs and outputs required along the entire supply chain associated with their production. A hybrid approach combines the first two approaches by combining process data with macroeconomic data to avoid the inherent truncations in the process approach and the high levels of aggregation in the EEIOA approach.

In this study, the Path Exchange (PXC) hybrid life cycle inventory analysis method was used to quantify embodied flows. Proposed by Treloar (1997), this method combines industrial data with average economic data to produce comprehensive embodied coefficients for building materials. The initial embodied environmental flows of a structural system is given by the following equation:

$$EF_{ss} = \sum_{m=1}^{M}(Q_{m,SS} \times FC_m) + \left(TFRTB - \sum_{m=1}^{M} TFR_m \right) \times C_{ss} \tag{2}$$

where: EF_{ss} = Embodied flow of structural system SS in flow unit (e.g., embodied energy in GJ); $Q_{m,SS}$ = Quantity of material m in the structural system SS (e.g., t of steel); FC_m = Flow coefficient of material *m*; *TFRTB* = Total flow requirement of the tall building sector in flow unit per Australian Dollar (AUD) (e.g., GJ/AUD); TFR_m = Total flow requirement of the input-output pathway representing material m (e.g. GJ/AUD); C_{ss} = Cost of the structural system in AUD.

3.3 Quantifying Cost

The initial cost of the tall building structural system includes the materials, transportation and construction process. The cost of a structural system is given by the following equation:

$$C_{ss} = \sum_{m=1}^{M} (Q_{m,SS} \times UC_m) + C_{t,ss} + C_{c,ss} \tag{3}$$

where: C_{ss} = Cost of the structural system in AUD; UC_m = Unit cost of material m; $C_{t,ss}$ = Transportation cost in AUD; $C_{t,ss}$ = Construction cost in AUD.

3.4 Comparing structural systems

In order to assess the range of structural systems that were considered, a score representing the premium-for-height would be assigned to each criterion. The criteria proposed in Section 1.1 are EE, EGHG emissions, EW and cost per gross floor area. Each criterion would be scored between 0 and 1, whereby a higher score would be achieved as the premium-for-height was further reduced.

The score assigned to a criterion for a structural system is given by the following equation:

$$S_{SS,i} = \frac{P_{II,i} - P_{SS,i}}{P_{II,i} - P_{I,i}} \tag{4}$$

where: $S_{SS,i}$ = Score for criterion i for the alternative structural system SS; $P_{II,i}$ = Value for criterion i for the base case *Phase II*; $P_{SS,i}$ = Value for criterion i for the alternative structural system SS; and $P_{I,i}$ = Value for criterion i for the base case *Phase I*.

Figure 2 illustrates the analysis of a 50-storey diagrid structural system for the EGHG emissions, EW, EE and cost per gross floor area criteria. Comparing the scores of all 12 structural systems listed in Section 1.2.2 facilitates the selection of structural systems for tall buildings.

4. DISCUSSION

The 'premium-for-height' framework, developed in the 1960s by Fazlur Rahman Khan, has had a significant influence on the tall building community. For the first time, Khan's framework proceduralised the structural design of tall buildings by attempting to decrease the material per gross floor area.

This paper identified the following limitations of this framework: (1) neglecting the environmental effects of structural system; (2) lacking the ability to compare structural systems of different materials; (3) not considering the cost of structural systems unrelated to the cost of materials; and (4) lacking integration into software tools currently available in the industry.

The embodied environmental flows are seldom considered in the design of tall buildings. When considered, existing studies use a process approach to quantify environmental flows, typically underestimating them by a factor of up to four compared to a hybrid analysis (Crawford *et al.*, 2018). Additionally, when establishing the structural equivalency between various structural systems, existing studies universally apply a simple static wind load to ensure an acceptable lateral deflection. However, the design of tall buildings is generally governed by the serviceability limit state requirements in response to the dynamic nature of lateral loads, such as wind and earthquakes.

It is possible that a reduction in the initial embodied environmental flows of a tall building's structural system might result in an increase in environmental flows at later life cycle stages and/or in other building systems. The sole consideration of initial embodied environmental flows for the structural system of tall buildings is a limitation of this study. Future studies should consider the environmental flows for the entire tall building across its life cycle.

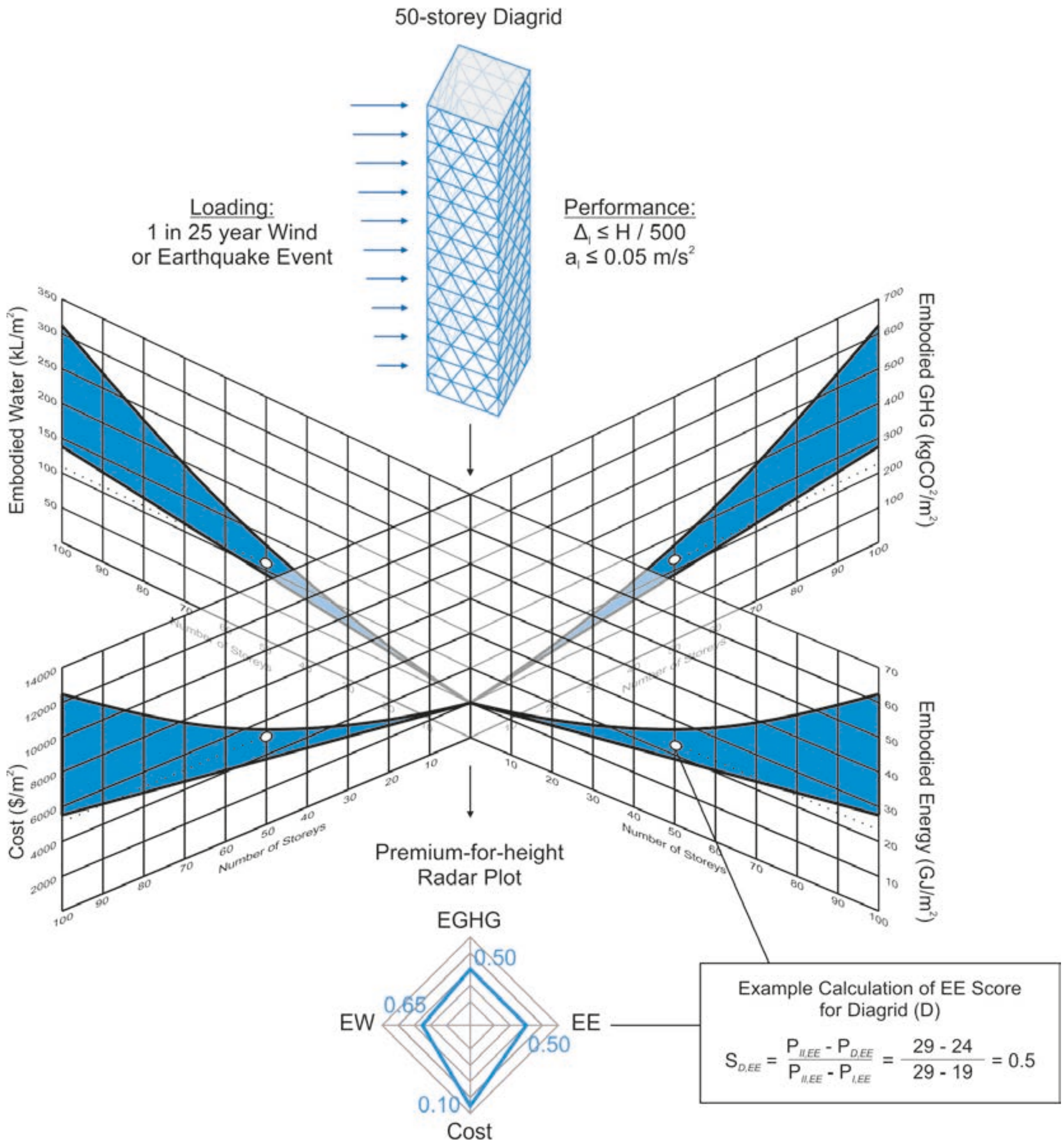

Figure 2 – Analysis of 50-storey diagrid structural system

5. CONCLUSION

This paper proposed going beyond Khan's 'premium-for-height' framework by presenting a revised theoretical framework that considers the environmental effects of structural systems, in addition to their cost, during early design stages. A hybrid approach to quantify environmental flows is proposed as it is shown to be the most accurate and comprehensive method globally. Additionally, advanced structural analysis is proposed to consider the dynamic nature of wind and earthquake in establishing structural equivalency among alternative structural systems.

The integration of structural design and environmental assessment, as proposed by this paper, has the potential to guide designers in making early stage design decisions that cost-effectively reduce the environmental effects of tall buildings. This research forms the basis of the revised framework for the design of structural systems in tall buildings.

References

Ali, M. M. and Moon, K. S. (2007) Structural Developments in Tall Buildings: Current Trends and Future Prospects, *Architectural Science Review*, 50(3), 205-223.

Cho, Y. S., Kim, J. H., Hong, S. U. and Kim, Y. (2012) LCA application in the optimum design of high rise steel structures, *Renewable and Sustainable Energy Reviews*, 16(5), 3146-3153.

Crawford, R., Bontinck, P.-A., Stephan, A., Wiedmann, T. and Yu, M. (2018) Hybrid life cycle inventory methods – A review, *Journal of Cleaner Production*, 172, 1273-1288.

CTBUH (2017) *CTBUH Year in Review: Tall Trends of 2017*, CTBUH, Chicago, Illinois.

Emporis Standards (2018) *High-rise Building (ESN 18727)*. Available from: Emporis Standards <https://www.emporis.com/building/standard/3/high-rise-building> (accessed April 16).

European Committee for Standardization (2011) *EN 15978:2011 Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method*, ed., BSI Standards Limited.

Foraboschi, P., Mercanzin, M. and Trabucco, D. (2014) Sustainable structural design of tall buildings based on embodied energy, *Energy and Buildings*, 68(Part A), 254-269.

Huberman, N., Pearlmutter, D., Gal, E. and Meir, I. A. (2015) Optimizing structural roof form for life-cycle energy efficiency, *Energy and Buildings*, 104, 336-349.

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L. and Acquaye, A. (2013) Operational vs. embodied emissions in buildings—A review of current trends, *Energy and Buildings*, 66, 232-245.

IPCC (2014) *Climate Change 2014: Synthesis Report*,Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 151.

Khan, F. R. (1967) Current trends in concrete high-rise buildings, *Symposium on Tall Buildings with Particular Reference to Shear Wall Structures*, Southampton, England, 571-590.

Khasreen, M., Banfill, P. F. and Menzies, G. (2009) Life-Cycle Assessment and the Environmental Impact of Buildings: A Review, *Sustainability*, 1(3), 674.

Mendis, P., Ngo, T., Haritos, N., Hira, A., Samali, B. and Cheung, J. (2007) Wind loading on tall buildings, *Electronic Journal of Structural Engineering*, 7(1), 41-54.

Moncaster, A. M., Pomponi, F., Symons, K. E. and Guthrie, P. M. (2018) Why method matters: Temporal, spatial and physical variations in LCA and their impact on choice of structural system, *Energy and Buildings*, 173, 389-398.

Ramesh, T., Prakash, R. and Shukla, K. K. (2010) Life cycle energy analysis of buildings: An overview, *Energy and Buildings*, 42(10), 1592-1600.

Roo, G. d. and Miller, D. (2000) *Compact cities and sustainable urban development : a critical assessment of policies and plans from an international perspective*, Urban planning and environment, ed., Ashgate, Aldershot, Hampshire, England; Burlington, VT.

Säynäjoki, A., Heinonen, J. and Junnila, S. (2012) A scenario analysis of the life cycle greenhouse gas emissions of a new residential area, *Environmental Research Letters*, 7(3), 034037.

Stafford Smith, B. and Coull, A. (1991) *Tall building structures: analysis and design*, 1 ed., Wiley-Interscience.

Standards Australia (2002) *AS/NZS 1170.0:2002 - Structural design actions : general principles*, AS/NZS 1170.0:2002, ed., Sydney : Standards Australia International ; Wellington : Standards New Zealand, 2002.

Stephan, A. and Stephan, L. (2014) Reducing the total life cycle energy demand of recent residential buildings in Lebanon, *Energy*, 74, 618-637.

Stevenson, M., Thompson, J., de Sá, T. H., Ewing, R., Mohan, D., McClure, R., Roberts, I., Tiwari, G., Giles-Corti, B. and Sun, X. (2016) Land use, transport, and population health: estimating the health benefits of compact cities, *The Lancet*, 388(10062), 2925-2935.

Treloar, G. J. (1997) Extracting Embodied Energy Paths from Input–Output Tables: Towards an Input–Output-based Hybrid Energy Analysis Method, *Economic Systems Research*, 9(4), 375-391.

Treloar, G. J., Fay, R., Ilozor, B. and Love, P. E. D. (2001) An analysis of the embodied energy of office buildings by height, *Facilities*, 19(5/6), 204.

Zhao, X. and Haojia, M. A. (2015) Structural System Embodied Carbon Analysis for Super Tall Buildings, *Procedia Engineering*, 118, 215-222.