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Embodied carbon premium for vanity height: A case for the exclusion of decorative spires in the design of tall buildings

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ABSTRACT

In measuring the height of a tall building, the Council on Tall Buildings and Urban Habitat (CTBUH) recognises three categories: "height to architectural top"; "height to highest occupied floor"; and "height to tip". The "height to architectural top" category, which includes decorative spires, is used to define the influential CTBUH annual rankings of the "World's Tallest Buildings". The inclusion of decorative spires in the category ranking has created an incentive for developers to maximise the vanity height of tall buildings, defined as the height difference between a tall building's architectural top and its highest occupied floor.

The aim of this paper is to demonstrate the detrimental influence of spires and, by extension, vanity height on the embodied carbon of structural systems for tall buildings. This influence is evaluated using three tall building scenarios of varying heights (50, 70, and 90 storeys). Two finite element models, with and without spires, are parametrically designed for each scenario. All the modelled structural systems comprise a reinforced concrete tube-in-tube lateral load resisting system. A hybrid life cycle inventory analysis approach is used to quantify the embodied carbon of spires as well as the resulting increase in the embodied carbon of structural systems.

The findings of this study indicate that even basic spires can lead to an increase of up to 14.2% in the embodied carbon of structural systems for tall buildings, underscoring the imperative to eliminate such elements in the design and construction of tall buildings to minimise overall embodied carbon.

1. Introduction

It is unmistakably clear that human activities have become major drivers of climate change. The latest report by the Intergovernmental Panel on Climate Change (IPCC) (2023) underscores this reality, indicating that greenhouse gas (GHG) emissions from human activities, spurred by population and economic growth, have reached their highest levels in history. In the context of global GHG emissions, the building sector emerges as a critical area, accounting for 34% and 37% of the total global energy use and GHG emissions, respectively (UNEP, 2022). Given the anticipated trends in urbanisation and population growth, these figures are expected to further escalate. However, this sector also presents one of the most promising arenas for rapid and substantial GHG emission reductions, utilising currently available technologies and well-established practices (IPCC, 2023).

Throughout their life cycle, buildings encompass diverse environmental flows: embodied, operational, and demolition phases. Embodied environmental flows cover a spectrum of processes, starting from the extraction of raw materials, progressing through the manufacturing of building materials, to the construction phase, and including the use and periodic replacement of materials over the building's life span. Operational environmental flows pertain to daily building functions like heating, cooling, ventilation, and lighting. Demolition flows are related to the deconstruction of buildings and the subsequent transportation of waste materials. While the focus of building regulations and efforts to enhance environmental performance has predominantly been on operational environmental flows (Giesekam et al., 2016; Ibn-Mohammed et al., 2013), it has been revealed that embodied energy could constitute up to 60% of the total life cycle energy demand of a building (Crawford and Treloar, 2003; Dixit et al., 2010; Huberman and Pearlmutter, 2008; Sartori and Hestnes, 2007; Stephan and Stephan, 2014; Yohanis and Norton, 2002). As the trend to minimise operational flows continues, the importance of embodied environmental flows in the life cycle of buildings is gaining increasing recognition (McManus et al., 2017; Säynäjoki

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et al., 2012).

The turn of the millennium has seen a drastic increase in the construction of tall buildings, driven by rapid urbanisation. Between 2000 and 2023, the world has witnessed a more than 550% increase in the number of buildings surpassing 200 m in height (CTBUH, 2023). Research indicates that the embodied environmental flows per unit of gross floor area in tall buildings can be significantly higher – up to 60% more than those in low-rise buildings (Du et al., 2015; Treloar et al., 2001). The reason for this is the heightened structural material needs to counteract compounding wind and seismic forces, a challenge in tall building design famously referred to as the "premium for height" by Khan (1967). Consequently, the embodied environmental flows of structural systems in such buildings comprise a major portion of their total life cycle embodied environmental flows, as outlined by Zhao and Haojia (2015), underscoring the need for focused design strategies to reduce these impacts.

The Council on Tall Buildings and Urban Habitat (CTBUH) is renowned as the preeminent authority on tall building height, holding the mantle of adjudication for the coveted designation of the "World's Tallest Building". The prominence of this height distinction is manifested not merely on a global scale, but it also extends to continental, regional, and city-level recognitions, with niche classifications such as "World's Highest Religious Space" and "World's Tallest Offset-Core Building" (CTBUH, 2023).

The defining moment in CTBUH's approach to height measurement came in 1996 during the contention between the Petronas Towers in Kuala Lumpur, Malaysia and the Sears Tower in Chicago, USA. Since then, the CTBUH's "Height Committee" opted for the "height to architectural top" as the criterion for the "World's Tallest Buildings" ranking. This criterion encapsulates decorative spires, measured from the level of the lowest significant open-air pedestrian entrance to the architectural top of the building. However, the inclusion of decorative spires in the category ranking of the "World's Tallest Buildings" has created a pervasive trend of maximising vanity height in tall building design. Vanity height is defined as the height difference between a tall building's architectural top and the highest occupied floor (CTBUH, 2013), and its pursuit poses significant environmental implications. In addition to the embodied carbon of the spires, the structural loads imposed by spires have the potential to increase structural material requirements and thus increase the embodied carbon of tall building structural systems.

Tall buildings are already categorised by an embodied carbon premium for height due to the compounding influence of wind loads and earthquake loads on structural material requirements. The pursuit of vanity height in tall building design further exacerbates this premium by creating a perverse incentive for designers to prioritise height over sustainability. Therefore, in response to the increasing environmental effects of urbanisation and climate change, it is essential to re-evaluate the inclusion of decorative spires in the design, construction, and height category rankings of tall buildings and to consider alternative design approaches that prioritise minimising potential effects on the environment.

1.1. Aim and scope

The aim of this paper is to assess the influence of decorative spires and, by extension, vanity height on the embodied carbon of structural systems for tall buildings.

Recognising the direct link between GHG emissions and climate change, this research adopts an embodied carbon emissions assessment (ECEA) approach. It aims to gauge the global warming potential from the added vanity height in tall buildings' structural systems. This method offers a balance, bypassing the intricacies of a full life cycle assessment (LCA) while providing enough accuracy for effective decision-making concerning resource usage and environmental impacts (Allacker, 2010; Chau et al., 2015; Oregi et al., 2015).

In the realm of structural systems, the design emphasis is traditionally on achieving the intended functionality with minimal maintenance and repairs, as outlined by Taranath (2017). Therefore, this study posits that the operational environmental flows related to structural systems are negligible and, thus, excluded from the scope of this analysis. Similarly, this research does not consider the demolition environmental flows of structural systems, as they are generally minimal, contributing about 1% to a building's total lifecycle environmental flows (Trabucco et al., 2015; Winistorfer et al., 2007).

While the primary emphasis of this study is on superstructures, it is important to acknowledge that foundations and other building systems also contribute to a building's total embodied carbon. Foundation design, complex by nature and heavily influenced by site-specific conditions and architectural decisions, varies widely in its embodied carbon impact. Research shows that the embodied carbon from foundations can range from a minimal 2% to as high as 26% of a building's total embodied carbon (Robati et al., 2021; Zhang and Wang, 2017). Therefore, the calculations of the embodied carbon premium for height in this paper are confined to the superstructure. However, it should be noted that including the substructure and the increased overturning moments would likely increase the embodied carbon premium for vanity height.

This study's assessment framework aligns with the European standard EN 15643:2021 (see Fig. 1), which delineates a building's life cycle into four distinct stages: product, construction, use, and end-of-life (European Committee for Standardization, 2021). Focusing on the initial embodied carbon (EC) associated with the product stage (A1-A3), this research aims to quantify the embodied carbon premium attributable to vanity height in the structural systems of tall buildings.

1.2. Notions and definitions

1.2.1. Life cycle assessment

Life Cycle Assessment (LCA) encompasses a comprehensive analysis of the environmental impacts linked with a product or service across its entire life span. This spans from the extraction of raw materials to processing, manufacturing, distribution, usage, and eventually to repair, maintenance, and end-of-life stages, including disposal, reuse, or recycling (Crawford, 2011). Essential inputs in this process are raw materials, energy, and water, while typical outputs involve waste and GHG emissions.

As per the ISO, 20060 (2006) guidelines, LCA consists of four distinct phases. The initial phase, goal and scope definition, clarifies the study's purpose and its boundary conditions. The subsequent phase, the life cycle inventory (LCI), involves the identification and quantification of inputs and outputs throughout the product or service's life cycle. The third phase, life cycle impact assessment, scrutinises the magnitude and significance of the potential environmental impacts of these inputs and outputs. The final phase, interpretation, entails analysing and drawing conclusions from the LCA findings.

For clarity and consistency, this study adheres to the terminologies defined in this section, including LCA, LCI, and the various LCA stages. This consistency is vital for comprehensively understanding the context surrounding the embodied carbon in the structural systems of tall buildings.

1.2.2. Tall buildings

As illustrated in Fig. 2, CTBUH suggests that the definition of a tall building is subjective and considered against one or more of the following categories:

1. Height relative to context;
2. Proportion; and
3. Embracing technologies relevant to tall buildings (CTBUH, 2017).

CTBUH also makes the distinction between tall, supertall and megatall buildings. A supertall building and a megatall building are defined

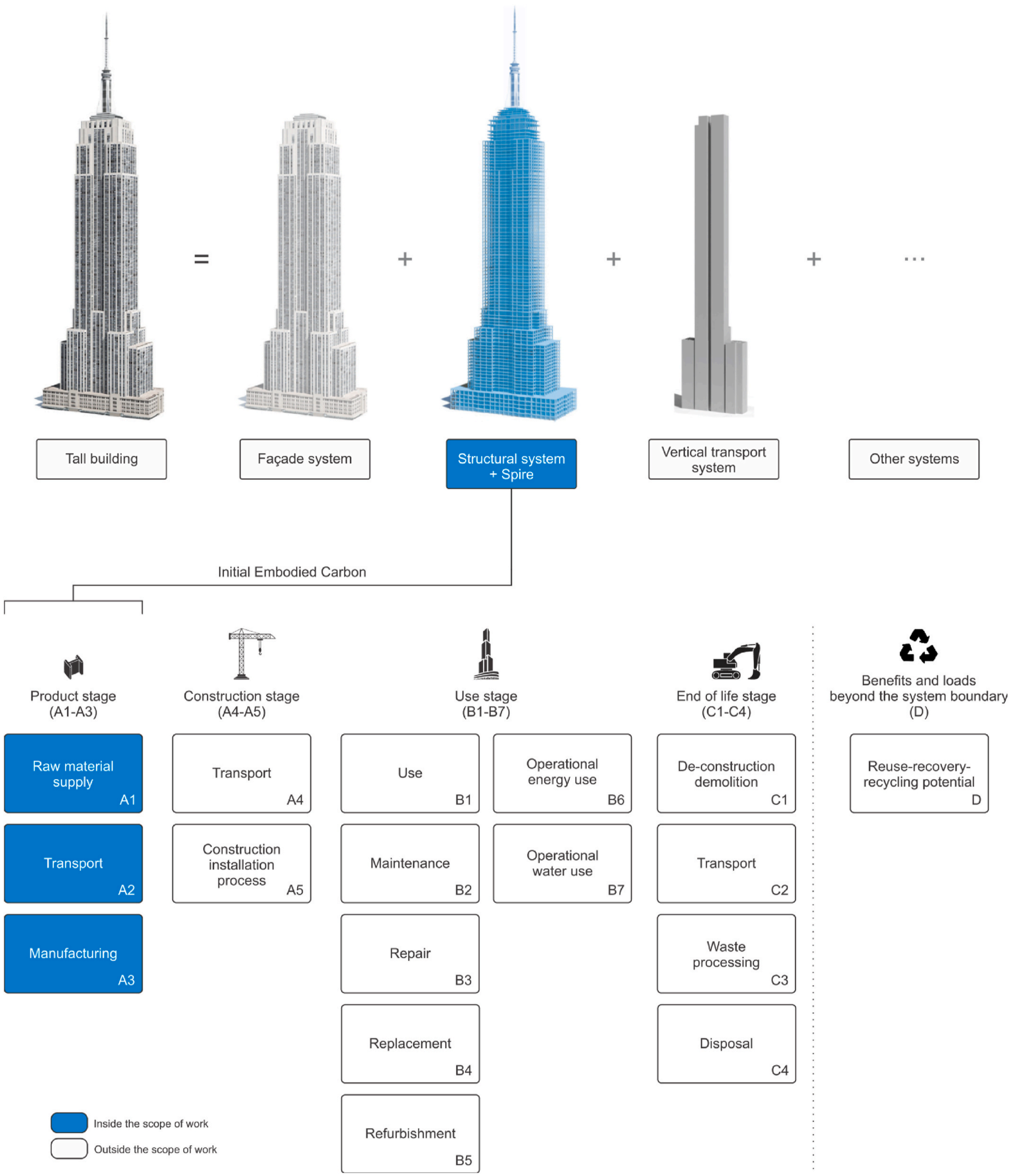

Fig. 1. System boundary of the study according to EN 15643:2021.

by CTBUH (2017) as tall buildings over 300 m and 600 m in height, respectively. Fig. 3 illustrates the distinction between tall, supertall and megatall buildings. As of September 2023, 211 supertall buildings have been completed worldwide. In the megatall category, three buildings stand completed, and a fourth has been structurally topped out, with an expected operational status by the end of 2023 (CTBUH, 2023).

Finally, in measuring the height of a tall building, CTBUH (2017) recognises three categories:

- Height to architectural top;
- Height to highest occupied floor; and
- Height to tip.

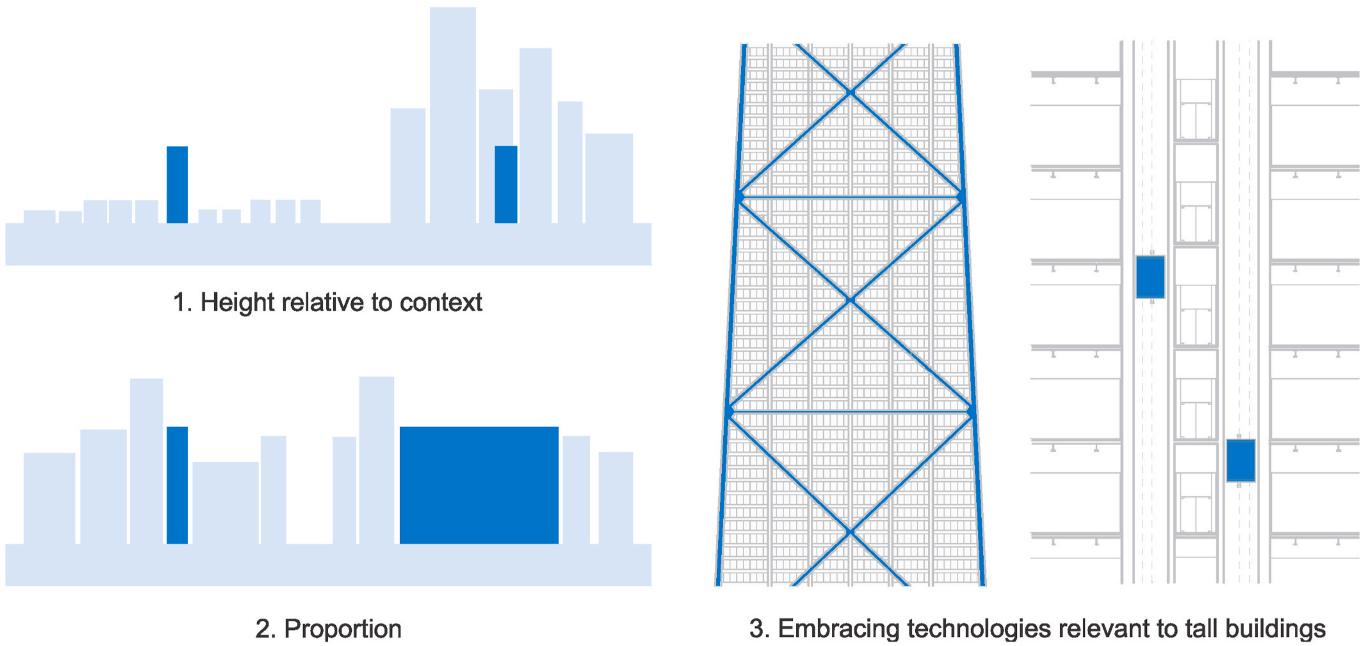

Fig. 2. CTBUH criteria for tall buildings (CTBUH, 2017).

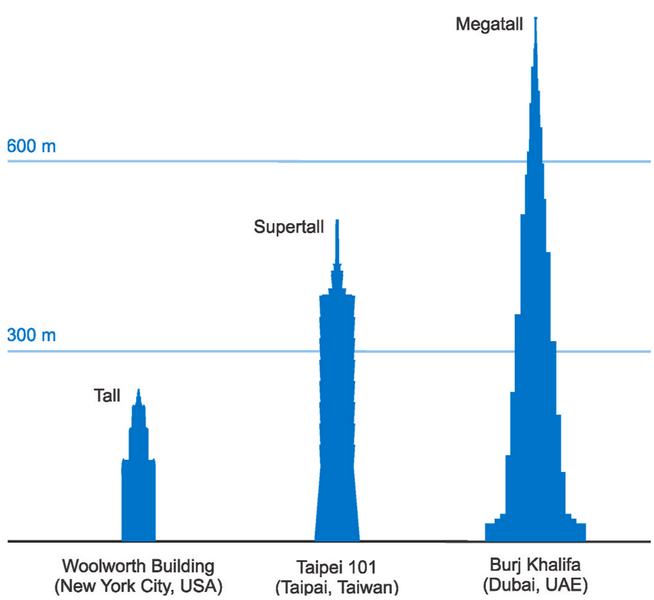

Fig. 3. Distinction between tall, supertall and megatall buildings according to CTBUH (2017).

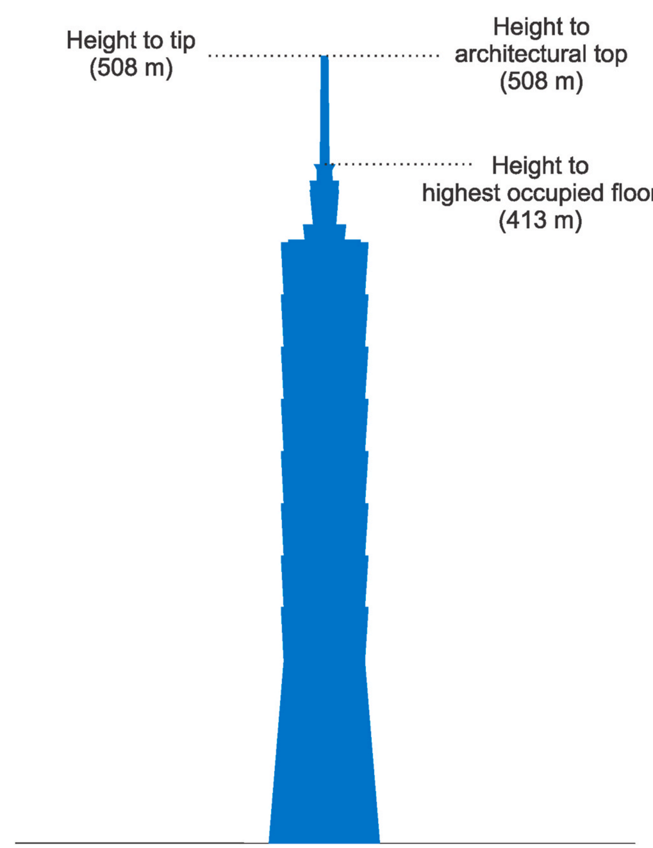

Fig. 4. Heights of Taipei 101 based on the different definitions of CTBUH (2017).

These different categories measure building height from the level of the lowest significant open-air pedestrian entrance (CTBUH, 2017).

The “height to architectural top”, which includes decorative spires, is the most widely used measurement height for tall buildings and is used to define the CTBUH annual rankings of the “World’s Tallest Buildings” (CTBUH, 2017). The “height to highest occupied floor” measures the building height to the finished floor level of the highest occupiable floor. Finally, the “height to tip” is the distance to the highest point of the building, irrespective of function. An illustration of building heights as applied to Taipei 101 is shown in Fig. 4.

1.3. Structure of the paper

This paper is structured into seven main sections. Section 1 introduces the aim and scope of the paper, followed by essential notions and definitions related to tall buildings and vanity height. In Section 2, the paper delves into the history of vanity height and the current prevalence of vanity height in various categories of tall buildings. Section 3 discusses the premium for height design framework by Khan

(1967) and introduces emerging research on the embodied carbon premium for height and other detrimental tall building characteristics. Section 4 presents the research method, including the processes of designing and quantifying the embodied carbon of spires and structural systems for tall buildings. Section 5 presents the results, followed by a discussion in Section 6 that interprets the results and addresses the limitations of the study. Section 7 discusses the implications of the findings on designers, planners and developers. The paper concludes in Section 8 with recommendations for further research to investigate the influence of vanity height on tall buildings of different characteristics.

2. Vanity height of tall buildings

2.1. History of vanity height

Historically, the quest to reach unprecedented heights has been a testament to human ambition. Whether through medieval Italian city towers or the lofty domes of religious sanctuaries, verticality served as a symbol of power, affluence, or spiritual aspirations. With the advent of the vertical passenger elevator in 1853, tall buildings began to redefine North American cityscapes. Emblematic of this trend, the Chrysler Building's distinct spire, erected in 1930 in New York City, was strategically designed to outdo the height of its rival, the 40 Wall Street Building (Wood, 2015).

The notion of vanity height was introduced in 2013 via a study conducted by CTBUH (2013), defining it as the distance between a tall building's highest occupiable floor and its architectural top. This conceptualisation is vividly illustrated by the proposed design of Kingdom Tower in Jeddah. The tower's striking spire, which represents over 30% of its height, is not only poised to eclipse the heights of many individual tall buildings but is intentionally designed to propel Kingdom Tower to the distinction of the world's tallest building, surpassing the height of Burj Khalifa (CTBUH, 2023).

2.2. Current prevalence of vanity height in the world's 100 tallest buildings

Data for the world's 100 tallest completed buildings, as of September 2023, were sourced from the *Skyscraper Center* — a comprehensive online database maintained by the CTBUH (2023). Notably, due to a data gap concerning the Tianjin Modern City Office Tower (ranked 95th), the dataset includes information from the soon-to-be-completed Merdeka 118 in Kuala Lumpur. This inclusion is justified given the tower's anticipated height of 678.9 m, positioning it as the second tallest globally upon its projected completion by the end of 2023 (CTBUH, 2023).

On average, buildings in the dataset exhibit a vanity height of 12.6%. Focusing on the world's four megatall buildings, the average spire height increases to 20.2%. Highlighting this trend, the spire of Burj Khalifa alone reaches an impressive 242.6 m, marking it as the tallest vanity height in the world. The combined spires of these four megatall buildings, if stacked, would exceed the height of the world's sixth tallest building as of September 2023. For a more detailed overview, refer Table 1 and the corresponding Fig. 5, which collectively delineate the five tallest building spires and their proportionate contribution to overall architectural height.

Geographically, the Middle East, particularly Dubai, dominates with the most pronounced vanity heights, averaging 17.0% of the architectural height. North America follows with 15.0%, and Asia, excluding China, averages 13.0%. In Europe, solely represented by Russian buildings in this list, the average is 10.7%, while China registers 10.4%. Notably, there are no structures from Africa, Australia, Central America, and South America in this context.

A detailed temporal analysis of the *Skyscraper Center* database categorises tall buildings into the following four eras: pre-2001 (marked by the September 11 attacks); 2001–2008 (characterized by the global financial crisis); 2008–2020 (defined by the onset of the Covid-19 pandemic); and the post-pandemic era. Intriguingly, the period from 2008 to 2020 registers the zenith of vanity height, averaging 12.9%, and this trend continues post-2020 at 12.7%. In contrast, the pre-2001 era sees the lowest average at 10.7%.

Considering the world's 100 tallest buildings, hotels exhibit the most pronounced spires, contributing 18.1% to their architectural height. Office buildings account for 15.2%, while residential buildings register at 12.6%, and mixed-use buildings at 10.3%.

Table 1
Comparative analysis of the world's tallest spires and their vanity height as a proportion of overall building height. Data retrieved from Skyscraper Center (CTBUH, 2023).

Building Name	Height to architectural top (m)	Height to highest occupied floor (m)	Spire height (m)	Vanity height as % of architectural height
Burj Khalifa	828.0	585.4	242.6	29.3%
Merdeka 118	678.9	502.8	176.1	25.9%
One World Trade Center	541.3	386.5	154.8	28.6%
Zifeng Tower	450.0	316.6	133.4	29.6%
Bank of America Tower	356.8	234.5	131.3	35.9%

2.3. Technical requirements and architectural significance of tall building spires

Vanity height encompasses all spaces situated above a building's highest occupiable floor. The term "occupiable" is defined by the CTBUH as a conditioned space crafted to safely and legally accommodate residents, workers, or other building users (CTBUH, 2017). This definition expressly excludes service zones or mechanical areas that receive only sporadic maintenance access.

Upon closer examination of the criteria for vanity height and occupiable floors, it becomes clear that spaces such as mechanical floors, elevator machine rooms, integrated evaporative towers, and other essential technical chambers are categorised under vanity height. However, to label these integral components as "vain" would misrepresent their vital role in the functionality of a building (Leung and Weismantle, 2008). Among the 100 tallest buildings surveyed, the minimal vanity height was recorded as a 6.5 m gap between the highest occupiable floor and the architectural top of the 85 Sky Tower in Taiwan. Two other buildings exhibited a vanity height of 9 m, potentially representing the most conservative spatial requirement above the highest habitable floor.

Furthermore, the tip of certain tall buildings not only adheres to these technical requirements but could also incorporate significant architectural spaces that enhance both user experience and the city's skyline. The China Resource Tower serves as a notable example. Its uppermost floor provides a public space, accentuated with a distinctive dome, adding 47.5 m to the building's height. While this architectural feature, constituting 12.1% of the building's total height, might fall under the category of vanity height, it introduces a unique architectural ambiance, marking a significant feature of the building. Many such structures around the world exemplify this harmonious blend of form and function, adding to the aesthetic and experiential richness of the building.

This research aims to differentiate between such architecturally significant designs and spires primarily added for achieving height benchmarks. Hence, while the presence of vanity height in some structures is both inevitable and architecturally meaningful, the critique primarily targets those spires incorporated mainly to surpass height

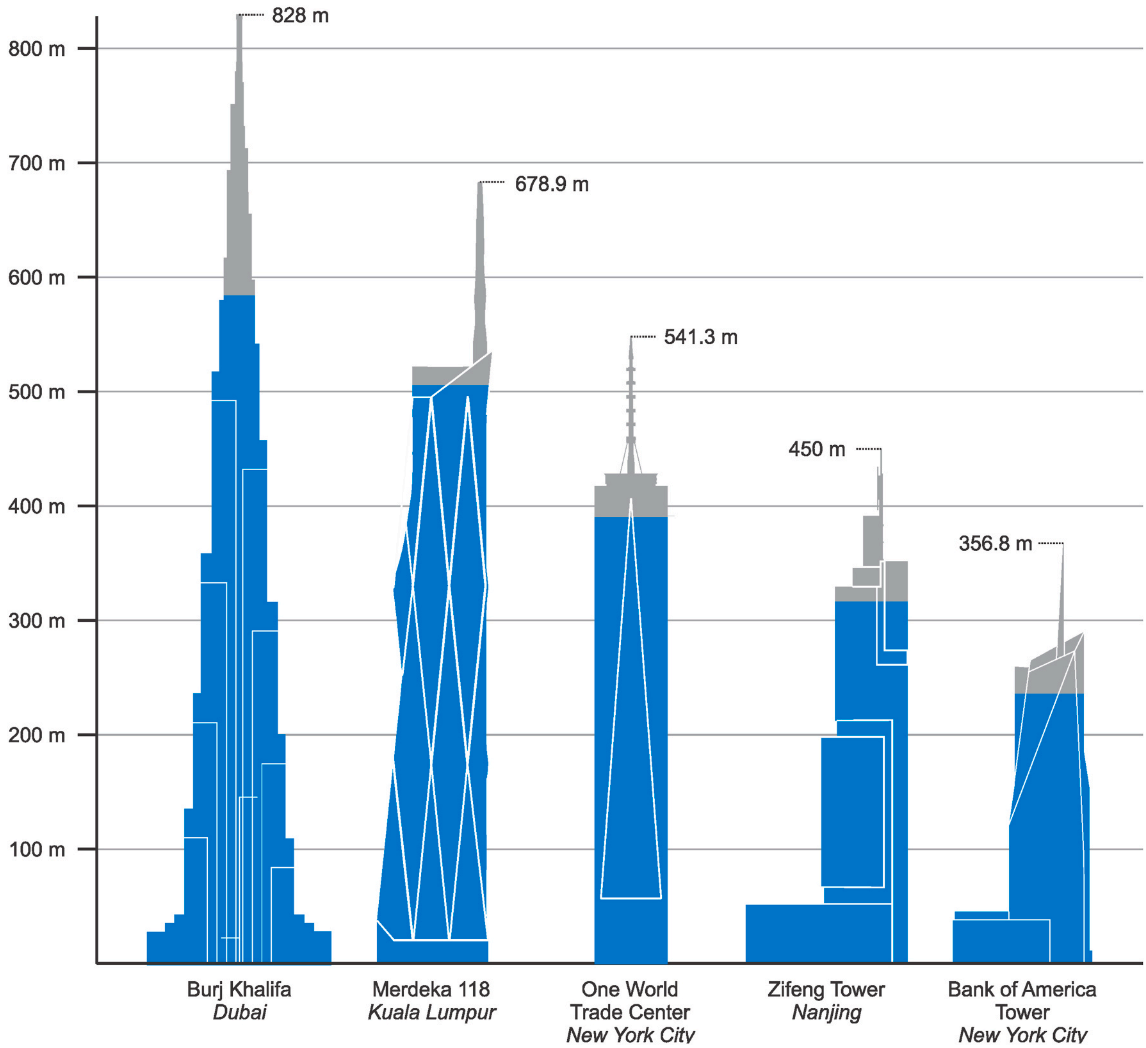

Fig. 5. Visual representation of the world's tallest spires, highlighted in grey. Data retrieved from Skyscraper Center (CTBUH, 2023).

records without offering substantial functional or aesthetic contributions.

2.4. Types of spires

A thorough analysis of the world's 100 tallest buildings has enabled a typological classification of spires. Visual aids, such as images and technical drawings of these tall buildings, were instrumental in segmenting the spires based on:

1. Spire Position:
   a. Centred: The spire's axis aligns with the building's central axis.
   b. Offset: The spire is displaced from the building's central axis.
2. Volumetric Shape:
   a. Continuation: The spire maintains the building's existing volumetric shape.
   b. Spike: A pointed protrusion distinct from the building's primary volume.
   c. Added Volume: An appended shape, potentially spherical, distinct from a spike.
3. Aerodynamic Properties:
   a. Low Drag: Typically seen in truss structures or spikes, where minimal surface area decreases wind resistance.
   b. High Drag: Occurs when elements, such as architectural cladding, augment the surface area, increasing wind loads.

To exemplify the classification system, the iconic Burj Khalifa demonstrates a centred spire that acts as a continuation of the building's form and has high drag properties due to its architectural cladding. The Petronas Towers' twin spires are intriguingly complex, positioned centred on the structures and incorporate both added volume (spherical sections) and spike elements. The architectural cladding suggests high drag aerodynamic properties.

The classification of the spires of the 100 tallest buildings is summarised in the following table (Table 2):

As discussed in Section 4 regarding the research method, the spires scrutinised in this study largely represent straightforward solutions for achieving vanity height. They employ a simple truss structure (classified as a spike) positioned offset from the building's central axis, unclad to minimise drag. It is paramount to note that spires falling under different categories may result in varied embodied carbon premiums. This variance can be attributed to differences in material properties of the spire itself and the accompanying structural loads they impose. The latter can influence the quantity of materials required in structural systems,

Table 2
Classification of spires in the 100 tallest buildings.

Classification Category	Options and counts
Spire Position	Centred (80); Offset (20)
Volumetric Shape	Continuation (66); Spike (19); Added volume (15)
Aerodynamic Properties	High drag (79); Low drag (21)

consequently impacting the associated embodied carbon.

3. Premium for height of tall buildings

During the 1960s, Fazlur Rahman Khan (1967) developed an innovative and highly influential design framework for the structural systems of tall buildings titled “premium for height”. This concept refers to the increase in structural material weight per net floor area (NFA) as building height increases, largely due to the compounded effects of lateral loads, such as wind and seismic forces. With the development of the “premium for height” framework, Khan (1967) sparked an era of structural design innovation by contriving an original means of assessing and enhancing the lateral efficiency of structural systems for tall buildings.

While the "premium for height" framework is widely recognised and applied in the realm of tall building design, it overlooks the environmental implications of structural systems. This framework, which assesses structural efficiency based on the weight of structural materials relative to NFA, inherently favours lighter structures, often disregarding their environmental impact. Research indicates that using lightweight structures can paradoxically lead to increased life cycle greenhouse gas (GHG) emissions in tall buildings’ structural systems (Foraboschi et al., 2014; Helal et al., 2019), primarily due to the higher embodied carbon intensities of the materials used.

Consequently, there is a pressing need to innovate and adopt structural design methodologies for tall buildings that focus on reducing environmental impacts, particularly in light of climate change mitigation objectives. Given the immediate and accumulative effects of GHGs on climate change, it becomes essential to prioritise upfront environmental considerations in structural design processes for tall buildings.

3.1. Emerging research on the embodied carbon premium for height and other detrimental tall building characteristics

An examination of existing literature revealed a total of 11 comparative life cycle assessment (LCA) studies of structural systems for tall buildings. These studies encompass a variety of building heights, ranging from 15 to 120 storeys, and are set in diverse geographic locations including Australia, South Korea, Italy, and China. The studies collectively examine an array of structural system typologies employed in tall buildings, such as rigid frames, braced frames, shear walls, outrigger and belt systems, and diagrid structures, and multiple structural materials like reinforced concrete, steel, and composite materials.

As seen in Table 3, existing studies that use LCA to compare alternative structural systems for tall buildings do not encompass an assessment of decorative spires.

Currently, there’s a notable gap in research regarding how vanity height affects the embodied carbon in the structural systems of tall buildings. In an era where climate change presents formidable challenges, comprehending every aspect of structural optimisation, particularly in terms of embodied carbon, is crucial. This understanding is key to enhancing the decision-making process in both architectural and structural design.

Table 3
Existing studies that use life cycle assessment to compare alternative structural systems for tall buildings.

Study	Storeys	Structural typology	Structural materials	Other varied parameters
Tae et al. (2011)	35	Shear wall	RC	Concrete grade
Cho et al. (2012)	30	Braced frame, Outrigger and Belt	Steel	Type of bracing system
Foraboschi et al. (2014)	20, 30, 40, 50, 60, 70	Shear wall	RC, Composite	Type of flooring system
Zhao and Haojia (2015)	70	Shear wall, Outrigger and Belt	RC, Composite	Number of outriggers and belt
Moussavi Nadoushani and Akbarnezhad (2015)	5, 10, 15	Rigid frame, Braced frame, Shear wall	RC, Steel	–
Trabucco et al. (2015)	60, 120	Shear wall, Diagrid	RC, Composite, Steel	Concrete grade and structural dimensions
Mavrokapnidis et al. (2019)	64	Braced tube, Tube in tube, Diagrid, Outrigger and Belt	RC, Steel	–
Helal, Stephan, and Crawford (2020a)	10, 20, 30, 40, 50	Shear wall	RC, Steel	Life cycle inventory methodology
Helal, Stephan, and Crawford (2020b)	5, 10, 15, 20, 25, 30, 50	Shear wall	RC	Structural design actions
Helal (2022)	5, 10, 20, 30, 40, 50, 60, 70, 80	Shear wall, Outrigger and belt, Braced tube	RC, Steel	–
Helal et al. (2023)	5, 10, 20, 30, 40, 50, 60, 70, 80	Shear wall, Outrigger and belt, Braced tube	RC, Steel	–
This study	**50, 70, 90**	**Tube-in-tube**	**RC, Composite, Steel**	**Inclusion of decorative spires**

4. Research method

To evaluate the impact of spires on the embodied carbon of structural systems for tall buildings, this study adopt a parametric modelling approach. Given the intricate nature of structural design for tall buildings, the research utilises finite element modelling and analysis. This method is essential to confirm that both the structural systems and decorative spires adhere to the necessary performance standards. The methods of structural analysis and design for the structural systems and decorative spires are presented in Sections 4.1 and 4.2, respectively. The material quantities of the spires and the structural systems are then converted to embodied carbon using a hybrid-based life cycle inventory analysis approach, as presented in Section 4.3.

4.1. Parametric modelling and analysis of structural systems

This section delineates the methodologies used for the parametric modelling and structural analysis of the tall building models. The finite element method, a widely respected numerical technique, breaks down complex engineering and physics problems into smaller, manageable segments, known as “elements.” This method is integral to structural engineering, especially for predicting how structures respond to various loads. For the analysis and finite element modelling of tall buildings in this research, the ETABS software by Computers and Structures Inc. (2018) has been chosen for its robustness and proficiency in structural design.

The study adheres to the guidelines set out in Australian Standard AS1170.1:2002 for residential structures. This involves applying a consistent imposed load of 2 kPa across the floor slabs of the models, accounting for the expected usage-related loads of the structures. Additionally, a façade load of 2.5 kN/m was applied to the perimeter beams in constructing the models. Complying with Australian Standards AS1170:2002, a superimposed permanent load of 1 kPa, representing the weight of non-structural elements like partitions, was also uniformly distributed across the floor slabs.

By applying these standards and utilising the finite element method, this study aims to model the structural demands of tall buildings accurately. This precision is vital for assessing the embodied carbon impact related to structural loads, especially in the context of understanding the broader implications of vanity height in tall building design.

To examine the influence of spires on the embodied carbon of structural systems in tall buildings, two finite element models were parametrically designed for each of the three building scenarios with varying heights (50, 70, and 90 storeys). This resulted in a total of six distinct finite element models. Three models, without spires, acted as base case models against which the remaining three models with spires were compared.

To focus on the effect of the spires, elements such as structural design methods, material properties, and geometric properties of the structural systems were held constant across all models. Each of the six structural systems is composed of a reinforced concrete tube-in-tube lateral load resisting system. The building core for all models was uniformly designated to occupy 20% of the total floor area as is common in current tall building architectural practice and trends (Xie et al., 2022). Fig. 6 provides 3-dimensional illustration of the standardised floor plan used across all models, while Fig. 7 displays schematic 3-dimensional illustrations of the six distinct models.

4.2. Parametric modelling and analysis of decorative spires

To examine the influence of spires across buildings of different heights (50, 70, and 90 storeys) and to align with common architectural practices, the height of the spires was set at approximately 16% of the respective structural system's height. Consequently, spire heights of 37.5 m, 55 m, and 70 m were established for the 50, 70, and 90-storey buildings, respectively.

Drawing from standard architectural designs, each spire was segmented into three parts, with the initial segment being of equal height across the models. The bay width remained consistent throughout and was positioned to the location of the columns. The widths for the three segments were designated as 7.5 m for the first, 4 m for the second, and 2 m for the third in all three models — 50, 70, and 90 storeys. By selectively altering only the height of the spire, this methodology has been tailored to isolate and provide an in-depth insight into how variations in spire heights specifically impact the embodied carbon of structural systems, without interference from other potential factors.

Fig. 8 provides a three-dimensional depiction of the three spires, distinctly illustrating the variations in height and respective bay widths. According to the classification system developed in Section 2.4, these spires can be characterised as offset in terms of spire position, spike in volumetric shape, and low drag concerning their aerodynamic properties.

Moreover, wind loads on tall structures become increasingly significant as building height rises. This increasing pattern in wind loads is primarily due to taller structures being exposed to higher wind speeds as they extend further into the atmospheric boundary layer, encountering air masses that are both more turbulent and faster. Given these considerations, it is imperative to calibrate the wind loads on the spires to ensure their structural adequacy. In accordance with the Australian structural design standard, AS1170.0, wind load pressures were determined based on building height. The spire of the 50-storey building was subjected to a lateral pressure of 3.5 kPa to account for wind load. This value was adjusted to 4.0 kPa for the 70-storey building and further to 4.5 kPa for the 90-storey structure, reflecting the increased demands posed by wind-induced forces on taller buildings.

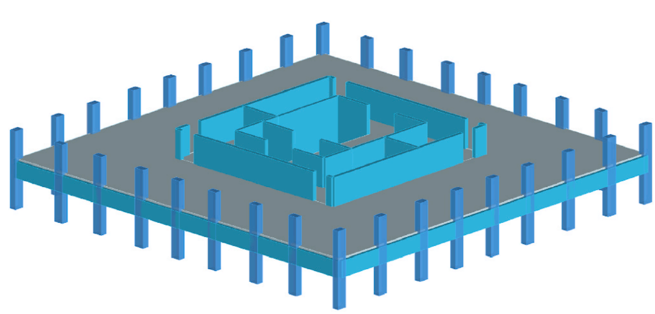

Fig. 6. Schematic 3-dimensional illustration of the standardised typical floor plan used across building models.

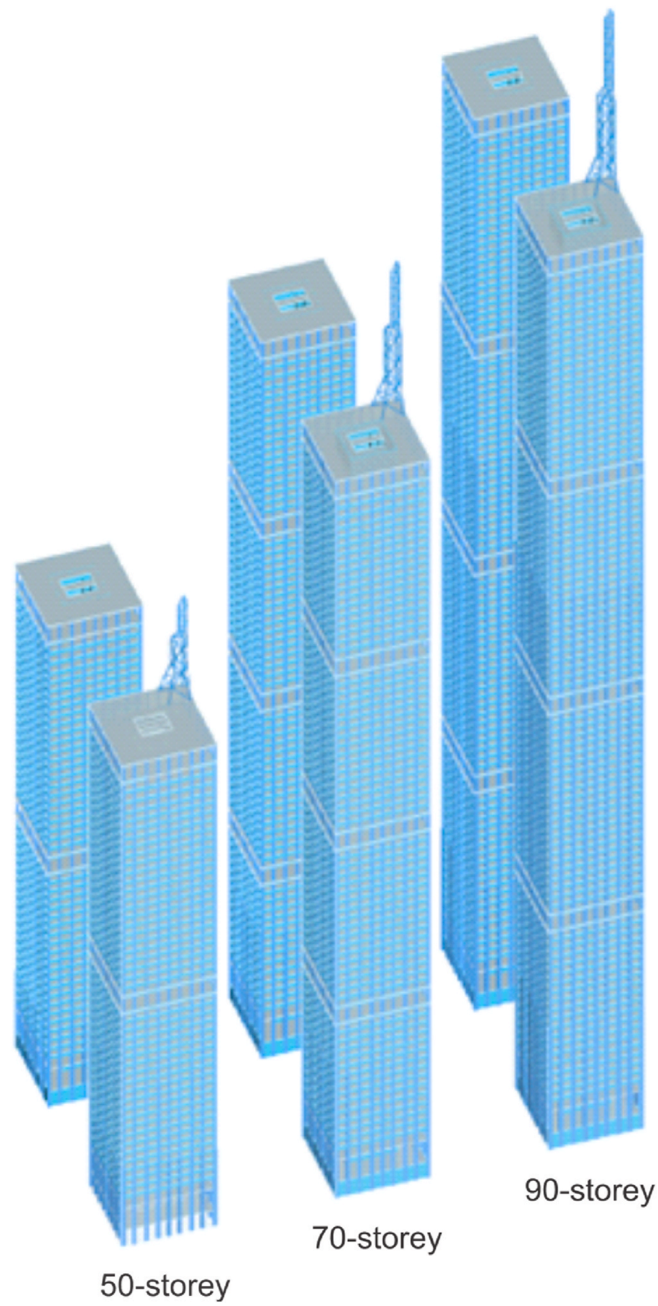

Fig. 7. Schematic 3-dimensional illustration of the six distinct building models.

4.3. Quantifying the embodied carbon of spires and structural systems

This section outlines the methodology used in this study to calculate the embodied carbon in structural systems and decorative spires of tall buildings.

To compile a Life Cycle Inventory (LCI), this study examines three

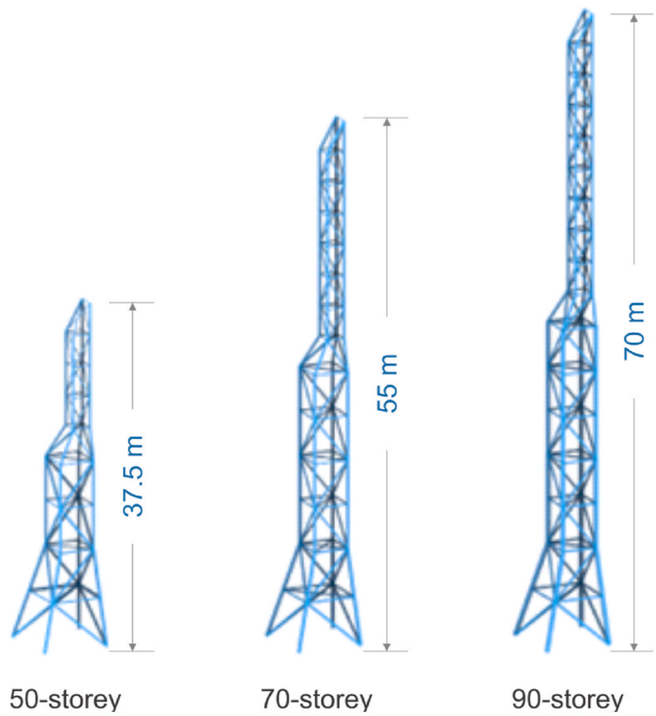

Fig. 8. Schematic 3-dimensional illustration of the three spires used in the design of the 50, 70, and 90-storey models. Note: all measurements are in metres.

primary methods: process analysis, environmentally-extended input-output (EEIO) analysis, and hybrid analysis. Process analysis focuses on the life cycle of a specific product or service, detailing its inputs, outputs, and environmental impacts (Finnveden et al., 2009). While accurate, it often falls short in fully capturing the product or service's supply chain, potentially underestimating the embodied energy in buildings (Crawford, 2008; Lenzen, 2000; Majeau-Bettez et al., 2011).

EEIO analysis, on the other hand, correlates financial flows with physical flows. It integrates economic input-output tables with environmental data, like energy usage or CO_2 emissions per unit of currency (Lenzen, 2000; Miller and Blair, 2009). This method reduces truncation errors common in process-based LCI but lacks specificity within product groups in an industry (Lenzen and Crawford, 2009; Majeau-Bettez et al., 2011).

To address these limitations, the study employs a hybrid LCI approach, notably the Path Exchange (PXC) method. Developed, refined, and automated by Treloar (1997), Lenzen and Crawford (2009), and Stephan et al. (2019), respectively, the PXC method offers global efficiency and comprehensive system boundary coverage.

This study utilises the Environmental Performance in Construction (EPiC) database for embodied carbon coefficients, compiled by Crawford et al. (2019) using the PXC method. The EPiC database, specific to Australia, is the sole hybrid database for construction materials within the country. The embodied greenhouse gas emissions (EGHGE) of structural systems in tall buildings are calculated using the equation:

$$EC_{SS+DS} = \sum_{m=1}^{M} \left(Q_{m,SS+DS} \times ECC_m\right) \qquad \text{(Eq. 1)}$$

Where EC_{SS+DS} = embodied carbon of structural system SS and decorative spire DS in kgCO_2-e; $Q_{m,SS+DS}$ = quantity of material m in structural system SS and decorative spire DS (e.g. steel in kg); and ECC_m = embodied carbon coefficient of material m (e.g. 2.86 kgCO_2-e/kg for steel).

It is crucial to note that the EPiC database employs an input-output-based hybrid LCI approach, reflecting Australia's unique economic and environmental context. This approach assumes that imported materials are based on domestic production conditions, acknowledging a potential area for refinement in future studies as data and modelling techniques evolve.

5. Results

In this section, the study's results are detailed. The material quantities from all six finite element models were gathered, translated into their embodied carbon values, and normalised per net floor area (NFA) for more effective comparison. Section 5.1 delves into how vanity height impacts the embodied carbon in structural systems. Additionally, Section 5.2 offers insights from a sensitivity analysis that evaluates the impact of life cycle inventory analysis on the results.

5.1. The influence of vanity height on the embodied carbon of structural systems

As mentioned in Section 4, the influence of vanity height on the embodied carbon of structural systems is evaluated using three tall building scenarios of varying heights (50, 70, and 90 storeys). Within each of these configurations, a pair of finite element models was constructed: one incorporating spires and the other excluding them.

Observations from Table 4, which isolates the analysis solely to the building models with spires, indicate that the spires account for a mere 1% of the structural systems' overall embodied carbon. This percentage remains consistent regardless of the varying building heights, ensuring the embodied carbon contribution from the spires maintains a constant ratio of 1% across all three building scenarios.

At a cursory glance, the seemingly inconsequential 1% contribution of spires to the total embodied carbon may induce the presumption that the influence of vanity height on the embodied carbon of structural systems for tall buildings is negligible. Such an interpretation, however, would be misleading. A more comprehensive understanding necessitates comparing the embodied carbon of the structural systems equipped with spires against their counterparts devoid of them. The true measure of the spires' influence is encapsulated not merely in the spires' intrinsic embodied carbon but, more critically, in the difference between the embodied carbon of structural systems with and without the spires.

To better assess the influence of vanity height, Fig. 9 depicts the resultant embodied carbon per net floor area (EC/NFA) of all six structural systems, which reveals a consistent pattern of exponential growth in EC/NFA corresponding to the height of tall buildings. This trend is observed irrespective of whether the buildings have spires. Such an observation aligns with Khan's "premium for height" framework, suggesting that resource consumption escalates with an increase in building height (Khan, 1967).

Fig. 9 illustrates a marked increase in EC/NFA in correlation with the height of tall buildings, observable in both structures with and without spires. This trend aligns with the "premium for height" framework initially posited by Khan (1967), which suggests heightened resource consumption in taller buildings, stemming from the cumulative impact of wind and seismic forces on their structural systems.

However, a marked differentiation is observed when comparing

Table 4
Embodied carbon comparison between the structural system and spire for tall buildings of varying heights (50, 70, and 90 storeys).

Building Model	Embodied Carbon of Structural System (tCO_2e)	Embodied Carbon of Spire (tCO_2e)
90-Storey (with spire)	76,221.89	666.39
70-Storey (with spire)	45,545.60	524.09
50-Storey (with spire)	24,574.44	245.71

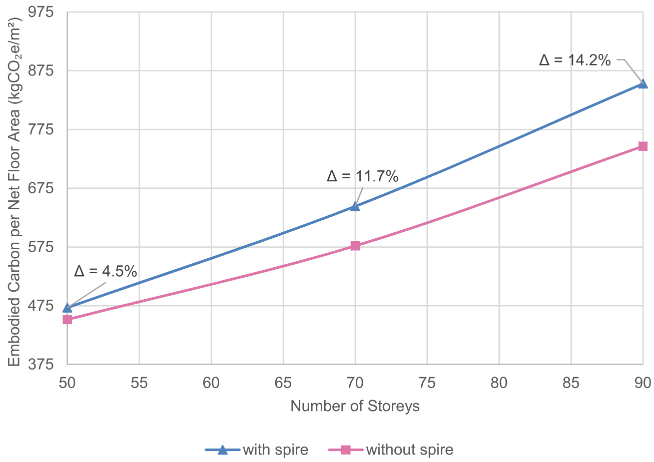

Fig. 9. Comparative analysis of embodied carbon per net floor area (EC/NFA) for structural systems with and without spires across varying building heights.

structures with spires to those without. Not only is there an upward shift in EC/NFA values for buildings inclusive of spires, but the exponential curve for these buildings also exhibits a steeper gradient. This variation is further highlighted by the growing differential: the 50-storey scenario sees a 4.5% increase in embodied carbon due to the spire. Contrastingly, the 70-storey and 90-storey scenarios witness an even steeper incline, with the spire contributing to an 11.7% and 14.2% increase in EC/NFA, respectively.

To better illustrate the compounding influence of vanity height on the embodied carbon of structural systems, Fig. 10 plots the increase in EC/NFA for each metre of vanity height against the actual vanity height for the three building scenarios. In the 50-storey scenario, the spire's addition (yielding a vanity height of 37 m) caused an increase of 28.74 tCO_2e of embodied carbon for each metre of vanity height. Conversely, in the 90-storey scenario, the spire's introduction, culminating in a vanity height of 70 m, led to an increase of 136.38 tCO_2e in embodied carbon for every metre of vanity height.

These findings shows that the influence of vanity height on the embodied carbon of structural systems in tall buildings is substantial and becomes increasingly pronounced as building height escalates.

Fig. 11 presents an analysis of the embodied carbon distribution across different structural element types, comparing their respective contributions to the overall embodied carbon for various building heights and configurations. Understanding this distribution is pivotal as it sheds light on which structural elements significantly contribute to the total embodied carbon of structural systems, and how their proportions vary with the inclusion of spires.

In both the 50-storey and 70-storey scenarios, the embodied carbon attributed to the slab accounted for the majority, regardless of the presence or absence of spires. However, in the 90-storey scenario, the core took precedence in both models (with and without spires), constituting the predominant source of embodied carbon. For the 50-storey models, the embodied carbon of the slabs represented 50% of the total embodied carbon of the structural system, irrespective of the presence of a spire. This proportion reduced to approximately 40% in the 70-storey model and further to 30% in the 90-storey models. This downward trend is also evident in band beams and coupling beams. Despite the total embodied carbon of the floor system (comprising slabs and beams) escalating linearly with building height, its proportionate share diminishes linearly.

In contrast, the embodied carbon from the core and columns exhibited an exponential increase with building height, evident in both structures with spires and those without. In the 50-storey scenario, the core constituted roughly 25%, and columns about 15% of the total embodied carbon of the structural systems. This fraction grew substantially in the 70-storey and 90-storey scenarios. Notably, the embodied carbon of the core and columns in structures with spires consistently surpassed that in structures without spires. Additionally, the rate of increase in embodied carbon of the core and columns in structures with spires outpaced that in structures without spires as building height increased. Thus, the results indicate that the core and columns, which are integral components of the tube-in-tube structural system, become increasingly susceptible to lateral forces upon the introduction of spires. To counteract this increased susceptibility, these structural elements need to be larger, which in turn results in a higher embodied carbon due to the greater volume of structural materials required.

Fig. 12 depicts the distribution of embodied carbon between the two primary structural materials: concrete and steel reinforcement. This comparison sheds light on their individual contributions to the total embodied carbon across varying building heights and configurations (i.e., with or without spires). In all three building scenarios examined, the embodied carbon associated with concrete consistently exceeded that of steel reinforcement. Furthermore, as building height increased, the rate of increase in embodied carbon from both concrete and steel

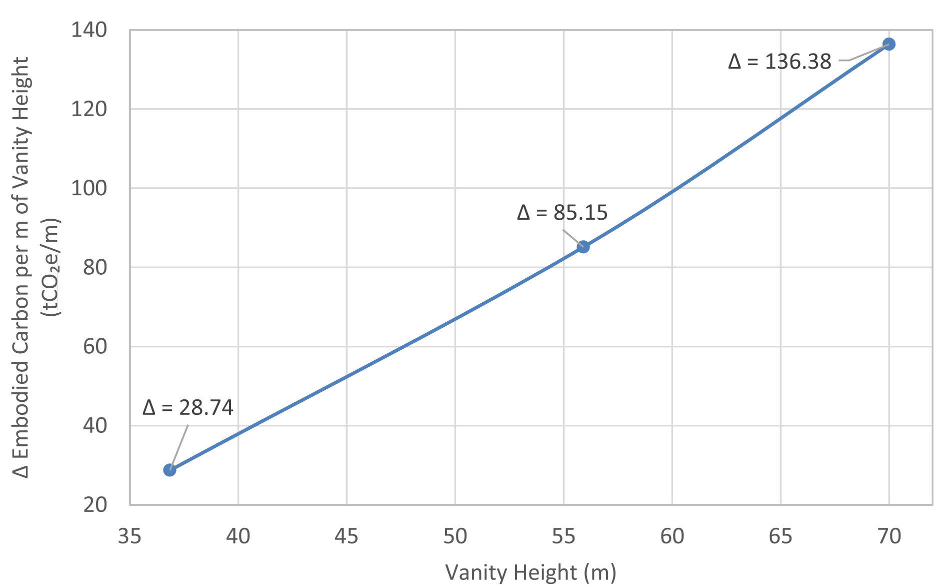

Fig. 10. Incremental increase in EC/NFA per metre of vanity height across the three building scenarios (50, 70, and 90 Storeys).

Fig. 11. Distribution of embodied carbon across structural element types for the three building scenarios (50, 70, and 90 Storeys) with and without the inclusion of spires.

reinforcement in structures with spires surpassed that in structures devoid of spires. This trend further highlights the increased structural material demands due to the inclusion of spires.

In summary, while spires contributed to only 1% of the overall embodied carbon of structural systems, their presence was shown to have a cascading impact on the embodied carbon of the structural systems. Structures with spires demonstrated a steeper exponential growth in embodied carbon, particularly within cores and columns, as building height increased. The results underscore the importance of understanding not just the direct contributions of architectural elements, such as spires, but also the cascading effects that vanity height can have on a building's structural system and material demands.

It is imperative to note that these findings specifically pertain to spires characterised as offset in position, spike in volumetric shape, and having low drag aerodynamic properties. Other spire classifications, especially those that are architecturally clad are likely to exert a more substantial impact on embodied carbon. This suggests that the presented results might represent the lower threshold of the actual effect.

5.2. Sensitivity analysis to determine the influence of life cycle inventory analysis methods

In this section, a sensitivity analysis is conducted to understand the influences of life cycle inventory approaches on the embodied carbon premium for vanity height of tall buildings.

To quantify the embodied carbon of structural systems, this work uses the environmental flow coefficients for building materials from the Environmental Performance in Construction (EPiC) Database compiled by Crawford et al. (2019). As discussed in Section 4.3, the EPiC Database and its underlying Path-Exchange (PXC) method for hybridisation were adopted since PXC is one of the most efficient LCI methods that preserves comprehensive coverage of the system boundary (Crawford et al., 2018).

In this section, the embodied carbon of the structural systems is recalculated using an alternative set of coefficients derived from Environmental Product Declarations (EPDs) specific to Dubai, UAE (Dubai Municipality, 2017). These coefficients, established through a

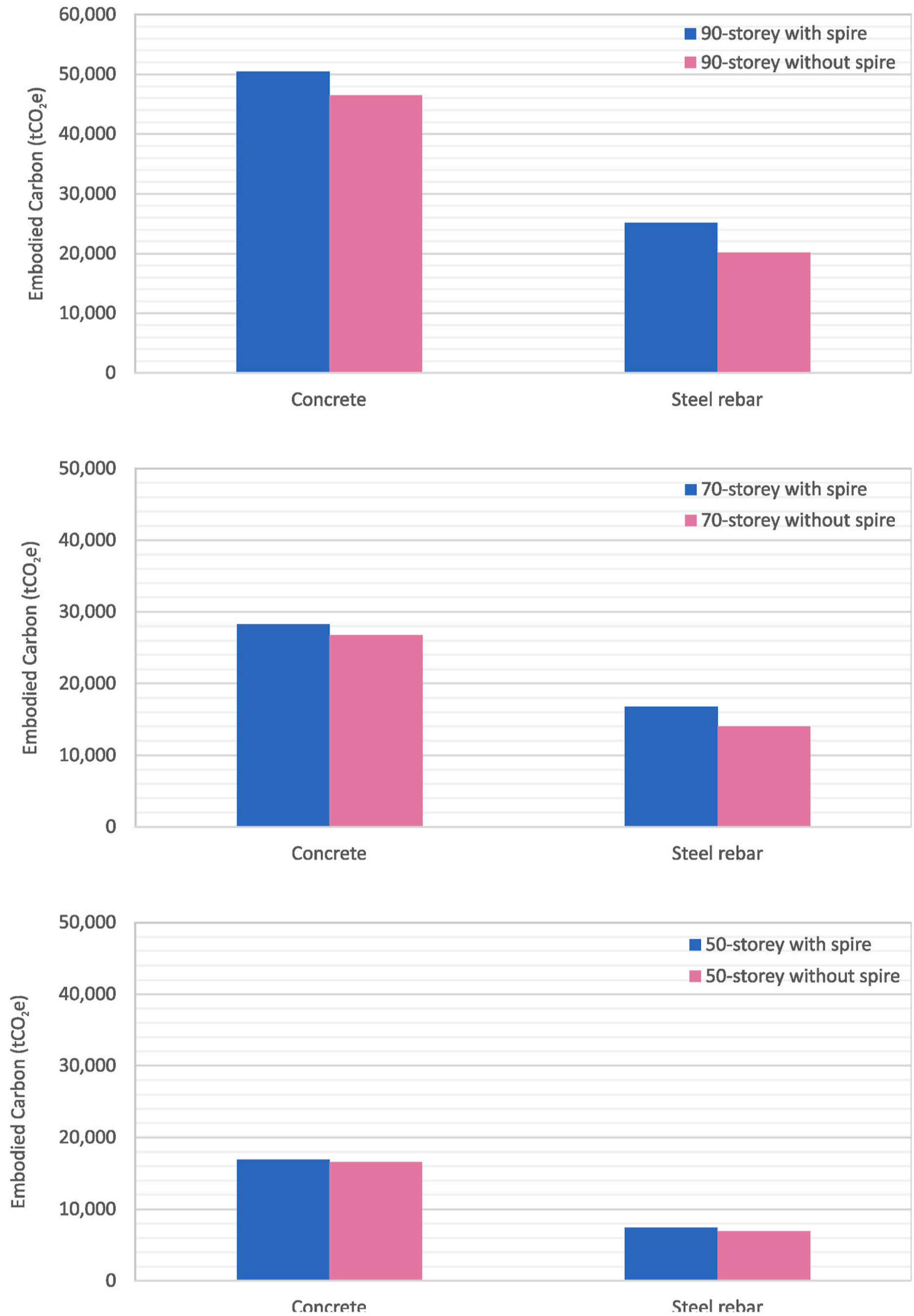

Fig. 12. Distribution of embodied carbon across structural materials for the three building scenarios (50, 70, and 90 Storeys) with and without the inclusion of spires.

process-based life cycle inventory analysis approach, encompass the same life cycle stages as the EPiC database (i.e., A1 to A3). Fig. 13 contrasts the embodied carbon per net floor area for the six building models, taking into account the embodied carbon coefficients from both the EPiC database and EPDs.

The findings suggest that using the EPiC coefficients results in embodied carbon values that are consistently about 60%–70% higher than those obtained when using the EPDs. This discrepancy aligns with existing research highlighting the potential truncation errors of process-based approaches, which might account for up to 80% (Crawford, 2008). Despite this differential, both data sources present analogous embodied carbon premiums for vanity height. For example, for the 50-storey building scenario, the addition of a spire led to an embodied carbon increase of 4.5% with EPiC and 6.8% with EPDs. In the 70-storey building, the premiums were 11.7% using EPiC and 14.6% with EPDs. For the 90-storey building, the respective figures stood at 14.2% with EPiC and 17% with EPD coefficients.

While the application of the EPiC database produced a concave curvature in the embodied carbon premium for height plots, employing the EPDs resulted in a convex curvature (see Fig. 13). Further insights from Fig. 14 reveal that the EPiC coefficients for concrete, underpinned by their hybrid life cycle inventory methods, manifests a steeper growth rate with increasing compressive strengths compared to the EPD coefficients.

This difference in growth rates between the datasets underscores the contrasting outcomes observed. It’s important to note that the building models from the 70 and 90 storey scenarios utilised higher grade concretes to adequately resist the increasing influence of lateral loads as

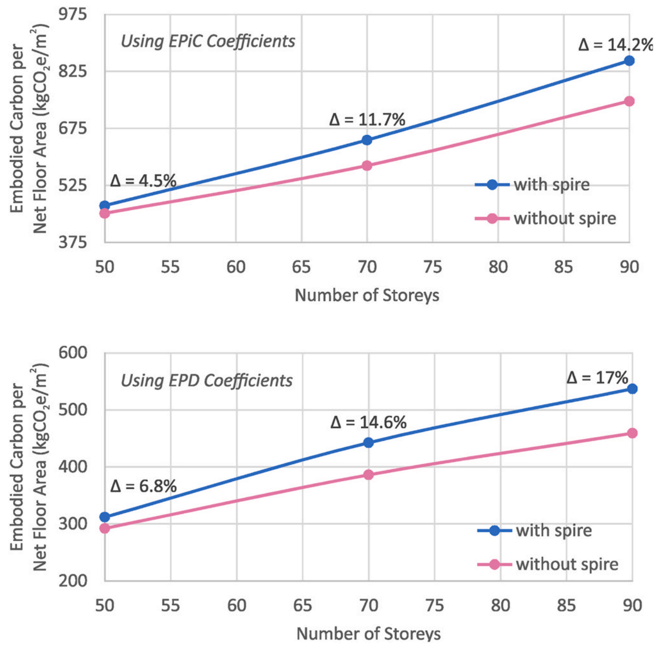

Fig. 13. Comparative analysis of embodied carbon per net floor area (EC/NFA) for the six building models using embodied carbon coefficients sourced from both the EPiC database and EPDs.

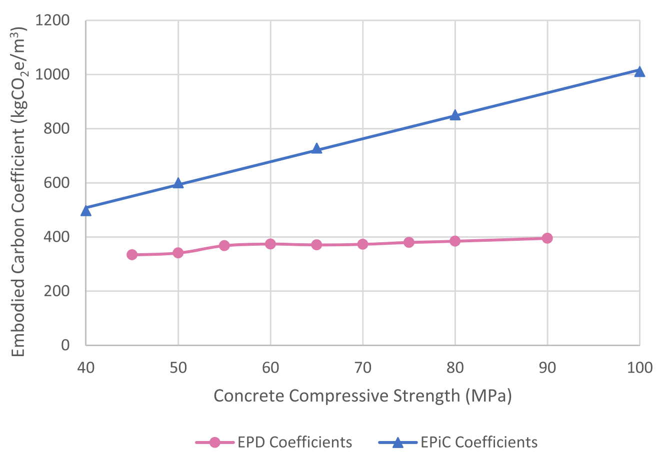

Fig. 14. Growth rate comparison of embodied carbon coefficients with increasing concrete compressive strengths, contrasting EPiC database and EPD values.

building height increased. Given that the EPiC coefficients exhibited a more pronounced growth rate with elevating concrete grades, the structural systems for the 70 and 90 storey buildings were associated with elevated embodied carbon coefficients. This, in turn, led these models to demonstrate an exponential relationship between embodied carbon and building height. These nuances highlight the profound implications of life cycle inventory method selection.

Such findings emphasise the critical importance of adopting consistent, transparent, and comprehensive life cycle inventory analysis methods when conducting comparative embodied carbon assessments of structural systems for tall buildings.

6. Discussion

This study aimed to elucidate the relationship between the vanity height of tall buildings and the resulting embodied carbon implications.

While the considered spires constituted only 1% of the total embodied carbon of the structural systems, their broader impact on the entire structural framework was markedly significant. In fact, for a 90-storey building, the influence of spires on the embodied carbon of structural systems was found to be as much as 14.2%. This underscores the occasionally overlooked significance of architectural features, such as decorative spires. Beyond their immediate embodied carbon contribution, these elements impose additional demands on the structural systems of tall buildings. The presence of decorative spires introduces not only additional vertical loads but also, and more critically, lateral loads. To counteract these forces, a greater quantity of structural materials is required, ensuring strength, stability, and adherence to serviceability requirements. Consequently, this increase in material use constitutes an embodied carbon premium for vanity height, which incurs a significant environmental toll, particularly when considered in aggregate across the numerous tall buildings that define urban skylines. Furthermore, it is imperative to emphasise that the findings presented in this research likely showcase some of the more conservative embodied carbon values for spires and structural systems. The spires evaluated in this study were characterised by their inherent simplicity, primarily due to their design as simple truss systems.

Moreover, the results depicted a clear exponential growth in embodied carbon per net floor area as building height increased. This pattern, which conforms with the "premium for height" framework by Khan (1967) and recent research on the life cycle assessment of tall buildings (Helal et al., 2023), poses pertinent questions about sustainable architectural practices, especially in urban contexts where tall buildings are prevalent.

The findings from the sensitivity analysis demonstrate the intricate nuances and disparities arising from different life cycle inventory analysis approaches. The differences in embodied carbon values between the EPiC database and the EPDs, coupled with the observed variances in the curvature of the premiums for height, underscore the challenges of comparative embodied carbon assessments. Such findings beckon the industry towards standardised practices and rigorous life cycle assessment methodological approaches, ensuring a higher degree of consistency and reliability in results.

Collectively, these findings accentuate the multifaceted nature of embodied carbon assessments in tall buildings. They provide not just quantitative metrics but also prompt critical introspection on architectural aesthetics, building practices, and overarching sustainability goals.

6.1. Limitations and potential improvements

This study, like any scientific endeavour, encounters certain limitations. Primarily, the scope of the findings is confined to the specific structural materials, structural typology, and floor plan geometry under consideration. Additionally, the outcomes are influenced by the various design strategies implemented for the decorative spires in tall buildings.

The research utilises Australian hybrid data to calculate the embodied carbon, reflecting the unique economic conditions and energy mix prevalent in Australia. While this geographical specificity might limit the direct applicability of the embodied carbon results, the structural material quantities derived through the structural analysis techniques remain highly pertinent. Future studies could adapt these material quantities to different regions by applying region-specific material coefficients for embodied carbon, especially in areas experiencing similar levels of lateral loads.

Future research endeavours could extend beyond the current study's parameters to augment the understanding of the embodied carbon premium associated with vanity height in tall buildings. Potential areas of expansion include broadening the system boundaries to encompass additional life cycle stages such as operational and end-of-life stages, as well as incorporating other building systems like facades and vertical transportation mechanisms.

7. Implications and significance of research

The determination of a tall building's height emerges from a complex interplay between planning allowances, prevailing economic conditions, available financing, and often, the ambitions of developers. While studies like those of Barr and Luo (2021) and Chau et al. (2007) have delved into the influence of economic drivers on tall building heights, the diverse set of variables remains multifaceted and intricate. The findings of this research may offer valuable insights for influential stakeholders and governing bodies, potentially influencing the prevailing trend of increasing vanity height through the incorporation of spires in tall buildings.

7.1. Implications for arbiters of tall building height

The Council on Tall Buildings and Urban Habitat (CTBUH) holds an authoritative position in defining the heights of tall buildings. Its annual publication, "A Year in Review," stands as an industry benchmark and is extensively used by media outlets to report on global construction activities within the tall buildings space. Commendation plaques from CTBUH, recognising height achievements, are proudly and prominently displayed at the entrances of numerous tall buildings globally.

Should the CTBUH decide to re-evaluate its criteria and adopt the "height to highest occupied floor" as the key criterion, it might encourage developers to place a heightened focus on sustainable material choices, thereby avoiding extraneous height enhancements associated with significant embodied carbon premiums, as demonstrated by this study. While the quest to construct ever-taller buildings is likely to continue, the parameters of this competition could see notable shifts. This transition could instil a more cautious approach among developers when seeking to set new height records, especially when factoring in the intricate challenges and increased costs associated with creating higher occupiable spaces. Additionally, in jurisdictions with embodied carbon regulations or pricing, the trend of adding non-functional spires might diminish, especially given their demonstrated carbon impact.

The inclusion of non-functional, decorative spires in height calculations—elements which this study has shown to contribute significantly to the embodied carbon of structural systems—merits reflection within the broader context of environmental impact. The role of CTBUH in establishing benchmarks for tall building heights carries with it the potential to influence design trends significantly. A recalibrated focus on 'height to highest occupied floor' could foster an industry-wide prioritisation of functional use over ornamental excess, thereby promoting designs that embody environmental stewardship. Such a recalibration would not only reflect a commitment to reducing embodied carbon but also support a shift towards sustainable innovation in architectural design.

7.2. Implications for structural engineers

Bold policy initiatives that aim to reduce the embodied carbon of new buildings and infrastructure have been implemented at a national level in France (Ministère de la Transition écologique & territoires, 2018), the Netherlands (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2012), Sweden (Swedish Transport Administration, 2012), Norway (City of Oslo, City of Bærum, City of Asker, City of Drammen, Ministry of Local Government and Modernisation, Norwegian State Housing Bank, 2019) and Finland (Ympäristöministeriö, 2017). Above all, structural engineers ought to maintain their knowledge of legislative and regulatory frameworks that will increasingly govern the structural design of new buildings and infrastructure.

By providing progressive, predictable, and feasible public policies, these initiatives are already instigating and incentivising change within the private sector. One prominent example is the Structural Engineering Institute, 2019; SE 2050) Commitment Program, which was launched in 2020 by the Structural Engineering Institute (SEI) of the American Society of Structural Engineers (ASSE) to ensure substantive embodied carbon reductions in the construction of new buildings (Structural Engineering Institute, 2019).

Corroborating the design optimisation principles of SE 2050, this work demonstrated that significant savings in the embodied carbon of structural systems for tall buildings - up to 15% - can be realised through the exclusion of decorative spires. Existing literature corroborates that such savings stem from design strategies that diminish the premiums for height, slenderness, and wide-open spaces in tall buildings (Helal et al., 2023).

7.3. Implications for developers

Property developers are essential to reducing the embodied carbons of the built environment. Through their customer base, real estate developers have a unique and significant influence on market forces related to the demand for construction materials. Leading real estate developers are increasingly pledging to adhere to industry guidelines focused on reducing the embodied carbon in new construction projects and infrastructure (World Green Building Council, 2019). Yet, there is a broad consensus that government-led measures, like implementing a carbon tax, are the most impactful strategies for reducing GHG emissions, particularly in the built environment (Freyre et al., 2020; K. Zhang et al., 2016).

Whether through carbon pricing or reduction targets and policies, property developers will have increasingly strong financial and regulatory incentives to reduce the embodied carbon of new buildings and infrastructure in the coming years. To meet emerging societal needs, developers are encouraged to act now and align their processes to the upcoming policies and interventions that aim to reduce the embodied carbon of the built environment (de Haan et al., 2014). Early adoption of such policies protects property developers from the challenges and costs of future transitions, whether through policy fines or competitive disadvantages.

It is widely agreed that the promotion of standardised embodied carbon calculation methods and design tools are needed to support real estate developers in meeting reduction targets (World Green Building Council, 2019). However, despite variations in embodied carbon calculation methods, this research underscores that omitting decorative spires from tall buildings consistently yields reductions in the embodied carbon of structural systems, with results varying between 14.2% and 17%, contingent upon the chosen source of embodied carbon coefficients.

7.4. Implications for urban planners

According to the United Nations Environment Programme (UNEP), the world will add 230 billion square metres of floor area for buildings by 2060 (UNEP, 2022). That is the equivalent of constructing a Burj Khalifa every 30 min for the next 37 years. To minimise the embodied carbon of new buildings, urban planners have an important role in adopting innovative and holistic land use policies, strategies and guidelines that produce functional and accessible urban environments.

Regulations that stipulate maximum building heights are a common feature of existing land use policies and planning schemes. Typically, the aim of such stipulations is to preserve the socio-ecological features of neighbourhoods and cities. However, central business districts, globally, have historically lacked strong regulations that govern the height limits of buildings. Given that tall buildings are not only characterised by an embodied carbon premium due to their height but also an additional premium attributed to vanity height, it is crucial for land use policies to critically evaluate the environmental implications of building height, including vanity height, on the embodied carbon footprint of structural systems.

Delving deeper into the broader implications on an urban scale, Dubai serves as an illustrative example. An analysis of the *Skyscraper*

Center database revealed that among the 119 buildings in Dubai standing over 200 m in height, only 65 had detailed information differentiating various categories of building height (CTBUH, 2023). The median vanity height for these 65 buildings was identified as 31 m. Extrapolating this median vanity height across all 119 buildings provides an aggregate vanity height of 3689 m for the city. With the average embodied carbon premium set at 83 tCO_2e per metre of vanity height, as determined in Section 5.1 and illustrated in Fig. 10, the cumulative embodied carbon premium for Dubai's 119 tallest buildings amounts to approximately 300,000 tCO_2e. It is vital to stress that this figure is a conservative estimate, given that many buildings in Dubai feature far more intricate and pronounced spires than the basic one examined in this study. In this context, Dubai's embodied carbon premium for vanity height translates to the annual emissions of 15,000 average United Arab Emirates (UAE) citizens. For additional perspective, the UAE has one of the world's highest per capita GHG emissions at 21.8 tCO_2e – dwarfing the 14.9 tCO_2e of the United States and 6.3 tCO_2e of European Union nations (International Energy Agency, 2022).

8. Conclusion

The construction industry faces a pressing need for transformative changes to address the urgent climate change mitigation goals and other environmental concerns (IPCC, 2023). While the focus has predominantly been on operational carbon in regulating and enhancing the environmental performance of tall buildings, recent studies have highlighted that the significance of embodied carbon is often overlooked (Dixit, 2017).

In the case of tall buildings, embodied carbon assumes greater importance due to the considerable impact of wind and seismic forces on the requirement of materials. In the context of the pressing climate crisis, it becomes imperative for engineers and designers to prioritise the reduction of upfront GHG emissions in the immediate future. The timing of emissions is critical; those released earlier in a building's life cycle have a more pronounced effect on Earth's radiative balance and atmospheric warming than later emissions (Levasseur et al., 2010; Säynäjoki et al., 2012; Schwietzke et al., 2011). Consequently, design strategies for tall buildings need to shift focus towards minimising the initial embodied carbon of structural systems to align with short-term climate and environmental mitigation targets.

The aim of this paper was to demonstrate the detrimental influence of spires and, by extension, vanity height on the embodied carbon of structural systems for tall buildings. This influence was evaluated using three tall building scenarios of varying heights (50, 70 and 90 storeys). Two finite element models are parametrically designed for each scenario, one with a decorative spire and another without. A hybrid life cycle inventory analysis method was used to quantify the embodied carbon of spires as well as the resulting increase in the embodied carbon of structural systems for tall buildings due to the influence of added structural loads.

In this study, the embodied carbon premium for vanity height was quantified, revealing a cumulative effect that intensifies with increasing building height. While spires directly contributed to a relatively small portion of the overall embodied carbon, their cascading impact on the structural systems emerged as both pronounced and significant, amounting to an increase of up to 14.2% for 90-storey buildings. Moreover, it's vital to highlight that the results derived from this research probably indicate the lower end of potential embodied carbon impacts for spires and the structural systems of tall buildings. The spires analysed, characterised by their streamlined design as simplified trusses, are likely among the least impactful in terms of embodied carbon. However, more architecturally elaborate spires could exacerbate the embodied carbon premium, extending it further to the structural systems.

Given the pressing challenges of growing urbanisation and its environmental implications, the findings of this paper underscore the need for a revision in architectural practices. Excluding decorative spires from the design and construction of tall buildings not only offers a tangible avenue to reduce immediate embodied carbon emissions but also marks a step toward more sustainable urban development.

CRediT authorship contribution statement

James Helal: Writing – review & editing, Writing – original draft, Validation, Methodology, Funding acquisition, Data curation, Conceptualization. **Dario Trabucco:** Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Dalibor Savovic:** Writing – review & editing, Software, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The finite element models and supporting data developed for this study can be freely accessed on Figshare at https://www.doi.org/10.26188/24247846.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142334.

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