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LEARNING FROM NATURE: BIOMIMICRY-INSPIRED BUILDING DESIGN FOR CARBON REDUCTION IN URBAN LIVING

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ABSTRACT

The built environment contributes significantly to global carbon emissions, with urban construction accounting for over one-third of total CO_2 emissions. With increasing urbanisation and climate concerns, effective methods for reducing building emissions are essential. This research evaluates biomimicry-inspired designs in reducing carbon emissions in urban high-rise residential buildings. A comparative analysis was conducted between a conventional 35-storey residential tower and a biomimicry-inspired model based on the human femur's structural efficiency and tree trunks' aerodynamic shape. Autodesk Carbon Insight was employed to assess carbon emissions, controlling variables such as material use, occupancy patterns, climatic conditions, and mechanical systems. The biomimicry-inspired design achieved a 48.76% reduction in embodied carbon and a 47.8% reduction in operational carbon, leading to an overall carbon emission decrease of 61%. These reductions were mainly due to structural optimisation, improved passive ventilation from stack effects, and effective solar shading. This study offers new theoretical insights by integrating form-driven design with carbon analysis at early design stages. The use of Autodesk Carbon Insight not only facilitates precise carbon quantification but also bridges a critical gap in evaluating biomimetic architecture beyond aesthetics or energy modelling. Practically, the findings introduce a replicable and scalable strategy for urban development that aligns construction with natural principles. As the urban environment continues to grow, the path forward must not resist nature but emulate it, because, as nature has long demonstrated, form follows function. This approach reframes design as a dialogue with the biosphere, marking a necessary shift toward regenerative and carbon-conscious architecture.

Keywords: *Autodesk Carbon Insights; Biomimicry; Carbon Emissions; Urbanization.*

1 INTRODUCTION

Urban centres are major zones of resource consumption (Secretariat of the Convention on Biological Diversity, 2012), and their continuous growth accelerates biodiversity loss and ecosystem degradation (Güneralp et al., 2013). Urban activities produce pollutants including wastewater, carbon emissions, smoke, dust, and solid waste, contributing

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significantly to environmental decline (Li et al., 2022). Fuel combustion further adds to atmospheric pollution, with notable emissions such as Sulphur dioxide (SO_2), particulate matter, and carbon dioxide (CO_2) (Liu & Wang, 2017). Urban environments are estimated to generate around 70% of global carbon emissions and are central to a range of socio-environmental challenges (United Nations Human Settlements Programme (UN-Habitat), 2022). Urban dwellers face heightened risks from the urban heat island (UHI) effect, with city regions registering higher temperatures than their rural counterparts (Patel et al., 2022). This is exacerbated by land use patterns, particularly energy consumption, transportation, and industrial processes, which intensify greenhouse gas emissions (Pataki et al., 2007). Urban areas, therefore, form a critical arena for addressing climate change (Hoornweg et al., 2011).

In response, design approaches such as biomimicry have gained traction as viable strategies for climate change mitigation in cities (Araque et al., 2021). Biomimicry involves applying principles observed in nature to inform the design of built systems (Pawlyn, 2019), offering pathways for sustainable architecture, urban planning, and infrastructure (Zari, 2021). It shifts design thinking by leveraging evolutionary intelligence embedded in biological systems, which have adapted to complexity, constraint, and efficiency over millennia. Biomimicry, therefore, not only informs resilient design but also realigns built environments with ecological processes. By studying organisms and ecosystems, designers can model urban forms capable of regenerating environmental health and responding flexibly to dynamic urban challenges (Zari, 2021). Despite its potential, biomimicry remains underexplored in the context of urban residential construction. While its application in other domains of the built environment is documented (Pawlyn, 2019; Woodward, 2023), its systematic integration into high-density housing remains limited. Yet, as Aanuoluwapo and Ohis (2017) suggest, nature offers tested solutions to disorder and complexity, traits now intrinsic to urbanization and climate volatility. Consequently, leveraging Biomimicry to mitigate the climatic impacts resulting from increasing urbanization and carbon emissions holds significant potential in the contemporary global context. Thus, this study investigates:

"How effective are biomimicry-inspired approaches in urban residential building construction projects for achieving net zero outcomes in the built environment?"

This study intends to assess the viability of biomimicry in the design and construction of urban residential towers by evaluating its capacity to reduce carbon emissions and contribute to scalable, low-impact construction solutions aligned with both ecological logic and net-zero carbon goals.

2 LITERATURE REVIEW

2.1 CARBON EMISSIONS IN THE BUILT ENVIRONMENT

According to the UN Environment Programme (UNEP) (2025), the construction sector in 2023 consumed 32 percent of global energy and was responsible for 34 percent of global carbon dioxide emissions. Operational emissions reached a peak of 9.8 gigatons, while embodied carbon emissions were approximately 2.9 gigatons. Although there was a slight reduction in embodied carbon emissions and an increase in renewable energy usage, which accounted for 17% of total building energy consumption in 2023, these efforts remain insufficient to achieve the goals of the Paris Agreement. The Intergovernmental Panel on Climate Change (IPCC) (2011) projected the sector's emissions would rise from 31% in 2020 to 52% by 2050. As a key driver of economic growth and resource consumption, construction significantly influences emissions, particularly through materials like cement and steel, which account for 18% of global emissions and generate substantial waste (Zhang et al., 2019). Notably, 2023 marked the first time since 2020 that emissions from the building sector plateaued despite ongoing growth, reflecting a 10% reduction in energy intensity and a 5% increase in renewables in final energy demand (Molloy, 2023). Looking forward, the sector could deliver 11% of global mitigation potential by 2035, roughly 4.2 gigatons of avoided CO_2 emissions, if aligned with the 1.5°C climate goal. Achieving this requires retrofitting existing buildings and designing new ones for sustainability. Biomimicry has emerged as a promising solution to support these efforts (Kennedy et al., 2015).

2.2 The Concept of Biomimicry in the Built Environment

Biomimicry offers a promising approach to reducing energy consumption and carbon emissions across various scales, from materials and components to entire buildings and cities (Pacheco-Torgal, 2015). In architecture and urban design, it supports sustainable and regenerative development (Hes & du Plessis, 2014). Nature operates on the principle of utilizing free energy, with most ecosystems relying on contemporary sunlight, which is recent solar energy converted into biomass through photosynthesis. Examples include seed pods dispersed by wind using air currents and marine mammals migrating by taking advantage of ocean currents (Zari, 2021). These systems serve as models of energy efficiency (Aanuoluwapo & Ohis, 2017), providing strategies to reduce fossil fuel dependence and emissions. Zari (2021) suggests designing urban environments to mimic ecosystem functions, which could help restore local ecosystems. Dicks et al. (2021) have proposed a forest as a model for urban planning and designing. Using trees as models for buildings not only suggests fitting each building with solar panels but also opens possibilities for advancements in biomimicry solar technologies. This includes water-splitting technologies that replicate many of the functional properties of leaves (Liu & Wang, 2017). Biomimicry also involves replicating the structure and function of biological forms, such as nests, focusing more on performance than aesthetics (Januszkiewicz & Alagoz, 2020; Uchiyama et al., 2020). This method enhances building performance by aligning with material efficiency and optimizing lighting and heating (Buck, 2017). The European Commission recognizes biomimicry as a key innovation area for climate adaptation and mitigation (Blanco et al., 2021).

2.3 Biomimicry as a Solution for Energy Efficiency and Carbon Reduction

Enhancing the thermal performance of building envelopes, particularly facades, is essential for reducing operational energy use while ensuring occupant comfort (Liao et al., 2022). Biomimicry offers nature-inspired strategies to lower energy demands for heating, ventilation, and lighting (Yuan et al., 2017). Badarnah (2015) introduced a framework for integrating biomimicry into building skins, addressing energy, comfort, water management, materials, and waste. Passive cooling and ventilation, another key application, draw on nature's efficiency (Khelil & Zemmouri, 2019). Zari (2021) notes that ecosystems demonstrate how energy-efficient systems can function without fossil fuels. For instance, researchers at the University of Rochester mimicked super-wicking plant leaves to enhance evaporation in cooling systems, achieving up to 500% greater efficiency (Smith et al., 2015). In the 1990s, biomimetic architecture gained prominence through landmark projects such as Zimbabwe's Eastgate Centre (1996). Emulating termite mounds to maintain stable indoor conditions without mechanical HVAC, Eastgate's use of natural ventilation and thermal mass reportedly reduced its energy consumption by roughly 90% relative to conventional buildings (Chayaamor-Heil et al., 2018). Another relevant example is London's 30 St Mary Axe ("The Gherkin"), which employs a passive ventilation system inspired by marine sponges to enhance energy efficiency (Aboulnaga & Helmy, 2022). However, such biomimetic innovations have seen limited application in high-density urban residential towers. This gap is particularly notable in light of rapid urbanization and the proliferation of high-rise housing, underscoring the need for further research on biomimetic strategies for high-density urban housing.

3 METHODOLOGY

This study adopted a phased methodological framework, progressing through four key stages. First, a comprehensive literature review was conducted to identify how biomimicry principles have been previously applied to reduce carbon emissions in the built environment. The second stage involved selecting a representative case study. The third phase focused on the digital development of two comparative building models: a conventional residential tower and a biomimicry-inspired counterpart. The final stage outlined the carbon quantification process using a performance-based analytical tool to assess both embodied and operational carbon emissions in a controlled simulation environment.

3.1 SELECTION OF THE CASE STUDY

A 35-storey apartment building located in the United States of America (USA), with a gross floor area of 28,000 m², was selected. This building is a standalone building where the structural system is reinforced concrete, and the external envelope consists of a double-glazed curtain wall façade. Figure 1 shows the architectural layout of the selected building, showcasing elevation, site plan, unit layout, and ground floor design.

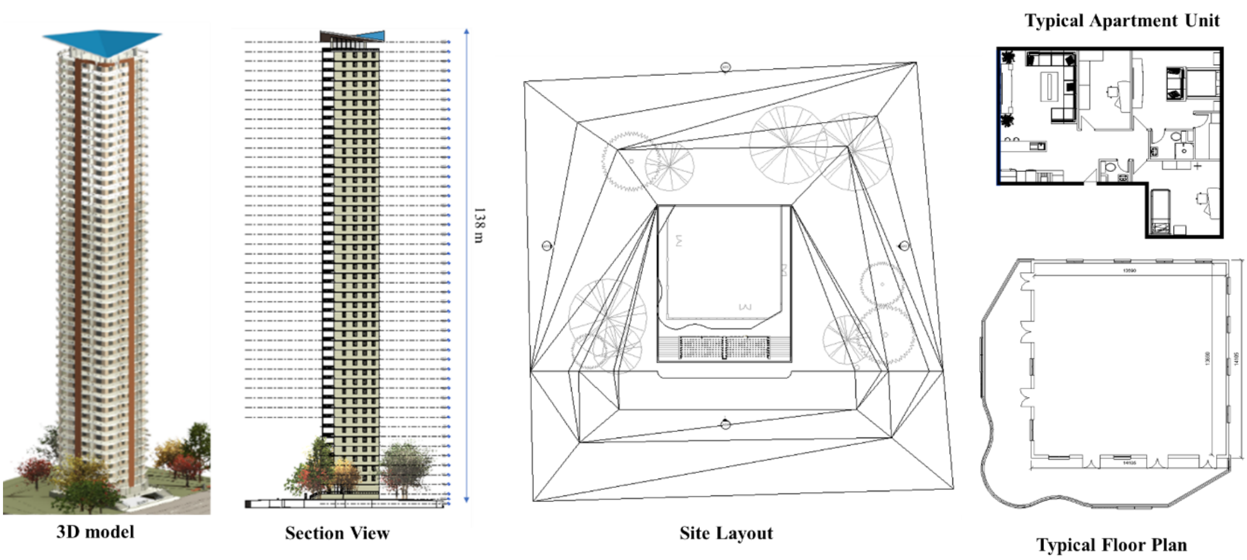

Figure 1: Architectural layout of the selected building, showcasing elevation, site plan, unit layout, and ground floor design

The choice of this building in the USA as a case study was guided by three principal considerations. First, the square form reflects a dominant typology in contemporary high-rise construction due to its structural simplicity, spatial efficiency, and adaptability (Steadman, 2006). Second, the selection of a USA based project aligns with the Autodesk Carbon Insights tool, which incorporates the EC3 database developed by the Carbon Leadership Forum in Seattle (Molloy, 2023). As this database relies on USA specific Environmental Product Declarations (EPDs), it enables a more precise assessment of embodied carbon within the local construction context. Lastly, the availability of comprehensive carbon data further supports the feasibility and relevance of this case study.

3.2 DEVELOPMENT OF THE BUILDING MODELS

Among different Building Information Modelling (BIM) software, Autodesk Revit was used to develop detailed digital representations of both the conventional and biomimicry-inspired designs. Geographic and climatic settings were adjusted in each model to simulate accurate carbon performance within a consistent environmental context. To maintain internal validity, identical building functions and spatial allocations were retained across both models.

3.2.1 Inspiration for the Biomimicry Building Model

A problem-based biomimicry approach was used to address the carbon-intensive nature of high-rise construction. This involved identifying carbon reduction as the central design challenge and analyzing natural systems for analogous solutions. The resulting design drew on the structural logic of the human femur and the aerodynamic form of tree trunks, both of which exhibit inherent efficiencies in load distribution and environmental adaptability. This translation of biological logic into architectural form was guided by structural engineering constraints and environmental performance objectives. Figure 2 shows the development process of the biomimicry inspired building model.

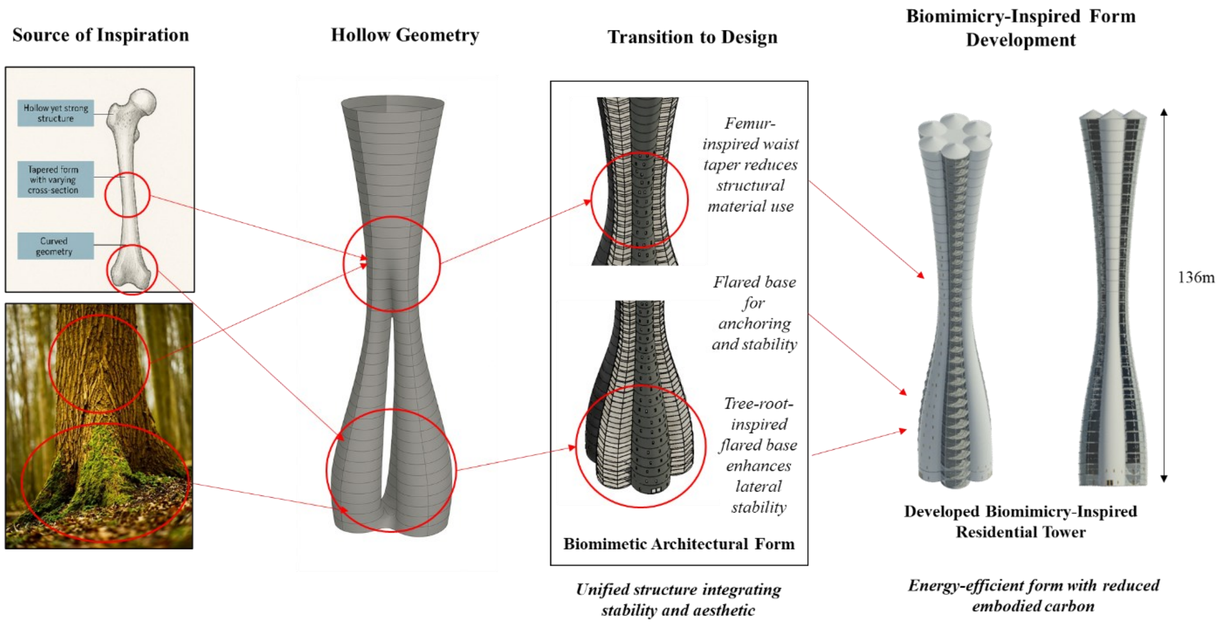

Figure 2: Development process of the biomimicry inspired building model

Figure 3 shows the floor plans and the roof plan views of the building.

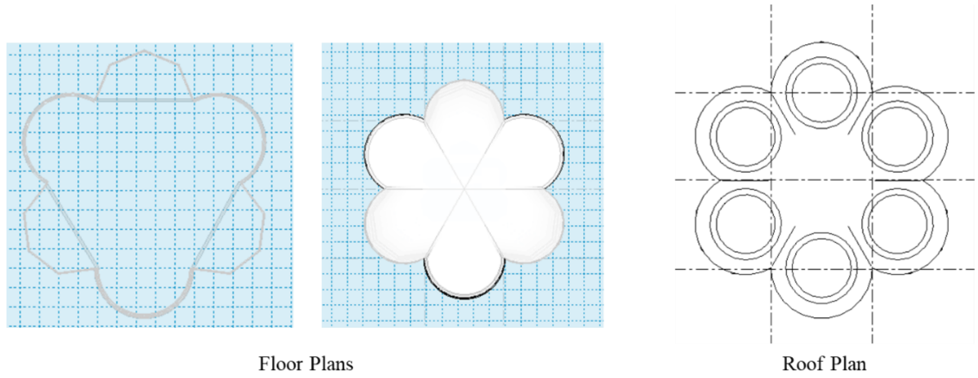

Figure 3: Biomimicry inspired building model: Floor plans and the roof plan views of the building

3.2.2 Architectural Features

The femur's hollow, tapered shaft and expanded ends exemplify how material can be distributed efficiently for maximum strength with minimal mass. This structural logic informed a building form with a narrow waist to reduce material demand and flared base and crown to enhance resistance against lateral forces such as wind and seismic loads. Meanwhile, the tree trunk, shaped by wind and gravity over time, inspired an aerodynamic and vertically optimized form, promoting passive ventilation, reducing wind pressure, and enhancing overall environmental responsiveness.

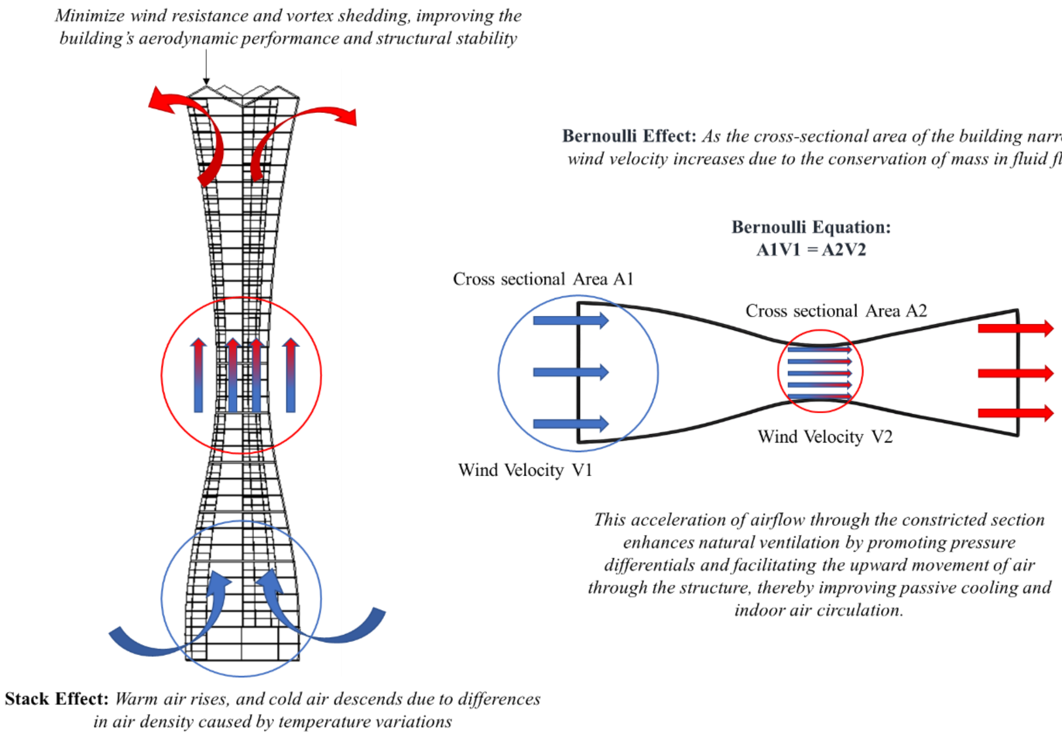

Figure 4: How the building form supports natural ventilation

Morphologically, the form supports natural ventilation via the stack effect, facilitated by the narrowing waist (see Figure 4), while the curved façade geometry minimizes solar gain. Inspired by spiral growth patterns in trees and bones, the building's subtle torsion facilitates wind redirection to enhance cross-ventilation. Orientation adjustments optimize daylight penetration and limit solar exposure on thermally sensitive façades, reducing reliance on artificial lighting and mechanical cooling. Collectively, these strategies embody a passive design logic derived from nature, where form and function converge to meet structural and environmental performance goals without relying on energy-intensive active systems.

3.3 Assumptions and Limitations

The analysis assumes consistent operational parameters for both models, including identical occupancy profiles, HVAC systems, lighting setups, and energy demands. Climatic conditions were held constant by applying a single weather dataset across both models. This controlled comparison allows isolation of the impact of form and structural logic on carbon performance.

3.4 Assessment of Total Carbon Emissions

Carbon quantification was performed using Autodesk Carbon Insight (Molloy, 2023), which integrates with Revit to evaluate both operational and embodied carbon metrics. The tool draws on data from the EC3 database, which aggregates third-party verified EPDs and material carbon intensities. By extracting quantities from the BIM models, it enables accurate forecasting of carbon outcomes at both design and procurement stages. Interactive dashboards provided by the platform support comparative assessment and facilitate informed decision-making on carbon reduction strategies. This capability is particularly valuable in early-stage design, where major decisions on form and materiality are made.

4 RESEARCH FINDINGS AND DISCUSSION

4.1 Comparison of Carbon Emissions between Conventional and the Biomimicry Inspired Building Models

Figure 5 and 6 illustrates the embodied, operational, and total carbon emissions calculated from Autodesk carbon insights for the two building models.

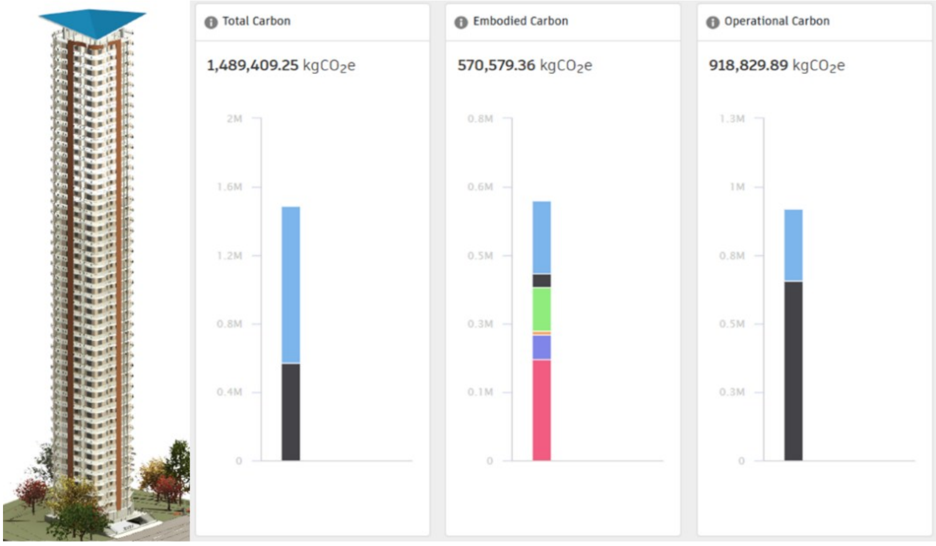

Figure 5: Embodied, operational, and total carbon emissions of the conventional building

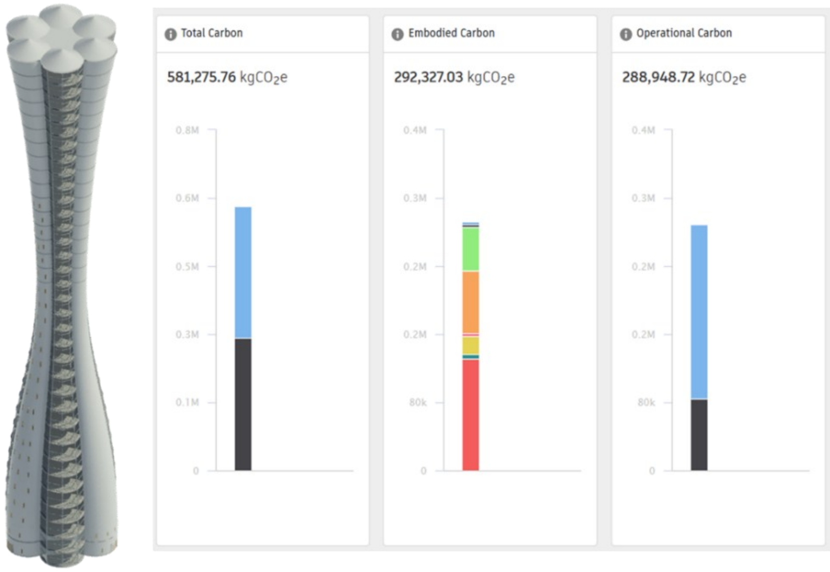

Figure 6: Embodied, operational, and total carbon emissions of the biomimicry inspired building

A comparative analysis of carbon emissions between the two models, based on data obtained from Autodesk Insights, is presented in the following sections.

4.1.1 The Comparison of Embodied Carbon Emissions

Figure 7 illustrates the embodied carbon emissions from the two building models.

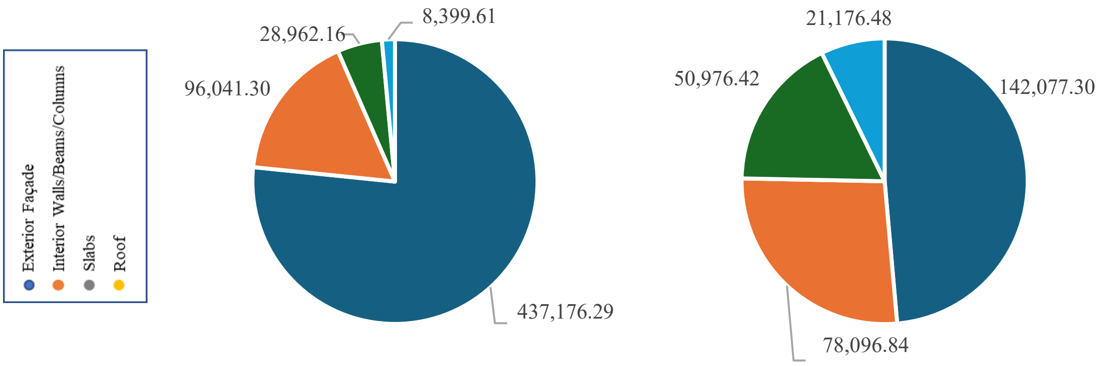

Figure 7: Embodied carbon emission from the two building models: Conventional building (Left) and biomimicry inspired building (Right)

The embodied carbon analysis shows a 48.76% reduction in the biomimicry-inspired design, with total emissions dropping from 570,579.36 kgCO_2e to 292,170.23 kgCO_2e (refer figure 5 and 6). Significant savings were achieved in the building envelope and structural elements like walls, beams, and columns. Although slab and roof emissions increased by 76% and 150% due to complex biomimetic geometries, the overall outcome highlights improved material efficiency through nature-inspired structural optimization.

4.1.2 The Comparison of Operational Carbon Emissions

Figure 8 illustrates the operational carbon emissions from the two building models.

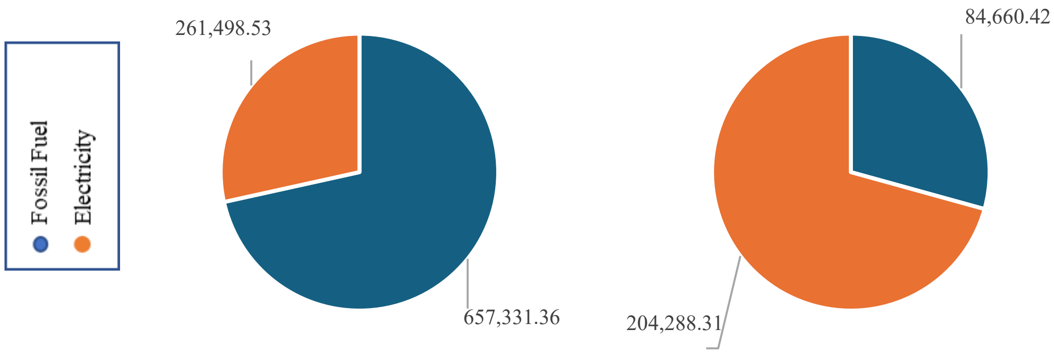

Figure 8: Operational carbon emission from the two building models: Conventional building (Left) and biomimicry inspired building (Right)

Operational emissions analysis shows that the biomimicry model reduced fossil fuel emissions by 87% (from 657,331.36 to 84,660.42 $kgCO_2e$) and electricity emissions by 22% (from 261,498.53 to 204,288.31 $kgCO_2e$). These reductions stem from passive design strategies, enhanced stack ventilation, solar shading from the flared crown, and optimized daylighting, achieved through geometric adaptation rather than mechanical systems.

4.1.3 The Comparison of Total Carbon Emissions

Figure 9 illustrates the total carbon emissions from the two building models.

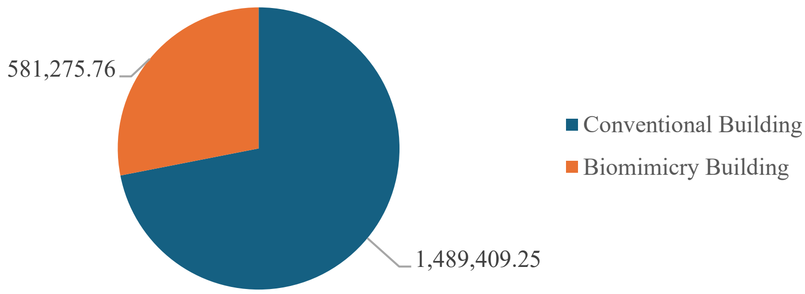

Figure 9: Total carbon emissions from the two building models

The cumulative carbon emissions underscore the impact of design form. The conventional model emitted 1,489,409.25 $kgCO_2e$, while the biomimicry-inspired counterpart emitted 581,275.76 $kgCO_2e$. This represents a total carbon reduction of 61%, reinforcing the potential for biomimetic design to influence both embodied and operational performance simultaneously.

4.2 DISCUSSION

These findings contribute to the emerging discourse on form-driven design as a primary vector for decarbonising the built environment. The 48.76% reduction in embodied carbon aligns with the assertion by Gu et al. (2024) that building form and structure have a direct influence on material-related emissions. Unlike most conventional studies that emphasise material substitution or efficiency at the procurement stage, this study isolates form as the primary variable. The use of the same materials, systems, and environmental conditions across both models reinforces the validity of this attribution. This isolation of form offers a rare empirical instance where geometry itself becomes the key decarbonising agent, an approach that remains underexplored in current lifecycle-based research methodologies. Comparatively, exemplar projects such as the Gherkin (Küçük & Arslan, 2020), Eden project (Woodward, 2023), and Sinosteel building project (Pawlyn, 2019) have demonstrated similar principles, using form to minimize material demand. However, these precedents often incorporate a combination of passive and technological strategies. What distinguishes the present study is its focus on form as a singular intervention, suggesting that biomimetic geometry alone, without significant changes in materials or building systems, can lead to substantial carbon reductions.

In contrast to integrated design approaches that blur the contribution of form with systems innovation, this model foregrounds the idea that the spatial and structural logic of nature, when translated into architectural massing, can independently drive carbon optimization. This reorients biomimicry from a symbolic or aesthetic discourse to one grounded in quantitative performance. Operational carbon results (refer to Section 4.1.2) further reinforce this. While much of the existing literature attributes energy efficiency to technological upgrades or system-level interventions, the findings of this study reinforce the argument made by Hanafi (2021) and Sudhakaran et al. (2017): that building form itself can regulate energy demand. Precedents such as the Esplanade Theatre, Eastgate Building, Sinosteel Plaza, and the Gherkin demonstrate similar outcomes, though only a few, including the latter two, attribute their efficiency primarily to aerodynamic and daylight-responsive geometries (Bijari et al., 2025). The Gherkin and Sinosteel projects report 80% and 75% energy improvements respectively comparable to the 47.8% operational carbon reduction achieved in this study. Crucially, these results are obtained without altering occupancy patterns, systems, or climatic conditions, underscoring the underexplored potential of early-stage morphological decisions in passive carbon mitigation. Notably, the biomimicry model integrates multiple passive functions, stack ventilation, solar control, and daylight optimisation, within a single, morphologically coherent form. This multifunctionality mirrors ecological principles, where natural structures often perform more than one function simultaneously, offering a resilient and adaptive logic for urban design.

Taken together, these findings challenge the current paradigm that treats architectural form primarily as an aesthetic or spatial determinant. Instead, they position form as a measurable variable in carbon performance modelling, with implications for lifecycle analysis, building codes, and early-stage design decision-making. This reframes biomimicry not as a conceptual exercise, but as a quantifiable design logic that may bridge the gap between ecological inspiration and environmental performance.

5 CONCLUSION

This study set out to examine the effectiveness of biomimicry-inspired architectural form as a mechanism for reducing carbon emissions in urban high-rise residential construction and contributing to net-zero objectives in the built environment. In the context of accelerating urbanization and intensifying ecological stress, the findings affirm that translating nature's structural and environmental logics into architecture is not only conceptually sound but demonstrably effective. Using a problem-based biomimetic approach, the study developed a tower form inspired by the human femur and the functional morphology of tree trunks. Carbon performance simulations using Autodesk Carbon Insight revealed a 48.76% reduction in embodied carbon and a 47.8% reduction in operational carbon, achieved without any modification to material specifications, systems, or occupancy parameters. These results isolate form as a critical, and often overlooked, determinant of environmental performance.

The study reinforces the central thesis that architectural morphology, when grounded in ecological intelligence, can supplant reliance on energy-intensive technologies by enabling inherent efficiencies. Passive shading, enhanced stack ventilation, and optimized structural load paths emerged not as afterthoughts, but as embedded outcomes of the building's biologically informed geometry. This aligns with successful precedents such as the Gherkin, Sinosteel Tower, and Eastgate Centre, positioning biomimicry as both scalable and practicable. Crucially, this research contributes to the growing body of knowledge in built environment that biomimicry transcends symbolic mimicry; it is a quantifiable, high-impact strategy with measurable environmental gains.

Future research may advance the potential of biomimicry by combining parametric simulations and multi-objective optimization techniques to explore how evolutionary geometries can shape scalable frameworks for decarbonized urban design. This approach positions biomimicry not as a niche innovation, but as a legitimate and reproducible strategy within the mainstream carbon discourse in construction. Further exploration into the integration of biomimetic geometry with advanced materials, modular construction methods, and responsive envelope systems could unlock additional performance gains.

Overall, this study advocates for biomimicry not as an optional aesthetic gesture, but as a strategic framework for design, one that repositions buildings as participants in natural systems rather than disruptors of them. As urban environments become the front line of climate mitigation, learning from nature offers not just a model for efficiency, but a philosophy of survival. In the pursuit of lasting, regenerative futures, it is time the built environment ceased to dominate nature and began to emulate it.

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