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Beyond Net Zero - SOM's Urban Sequoia Building Concept and Technologies for Future, Regenerative Cities

Mina Hasman[1], Jiejing Zhou[2†], Alice Guarisco[3], Nicholas Chan[3], Alessandro Beghini[3], Zhaofan Li[2], Michael Cascio[3], and Yasemin Kologlu[3]

[1]*Skidmore, Owings & Merrill (Europe) LLP*
[2]*Skidmore, Owings & Merrill (Shanghai) Architects Co. Ltd., China*
[3]*Skidmore, Owings & Merrill (USA) LLP*

Abstract Cities cover only 3% of the planet's surface, yet they are responsible for more than 75% of the global emissions. Given the projected urban built area will double by 2060, the carbon emitted from cities will further increase. SOM proposes the Urban Sequoia concept, for buildings that go beyond 'net zero' and absorb carbon from the atmosphere. This concept combines multiple strategies, including the use of an optimised building form with a highly efficient structural system, modularized prefabrication techniques, holistic integration of facade, MEP and interiors' components, bio-based materials, and Direct Air Capture (DAC) technology, to reduce a 40-storey building's whole life cycle carbon emissions by more than 300% over a 100-year lifespan. Calculations of embodied carbon emissions are performed with SOM's in-house Environmental Analysis (EA) Tool to demonstrate the effectiveness of employing Urban Sequoia's design strategies in the design of new buildings using current technologies.

Keywords Urban Sequoia, carbon absorption, bio-based materials, Direct Air Capture, EA Tool

†Corresponding author:
Jiejing Zhou
E-mail:
jiejing.zhou@som.com

1. Introduction

Urban Sequoia responds to an urgent need to rethink the design and construction of the built environment. Only 3% of the planet's surface is covered by cities, yet the world's urbanised areas generate about 75% of all global carbon emissions (Hasman, 2023, p.74). To accommodate increasing populations, the United Nations has predicted that another 230 billion square metres of building stock will be needed in cities by 2060 (Global Alliance for Buildings and Construction, 2021, p.29). To meet this goal, SOM has started to think of buildings as living organisms that can significantly reduce embodied carbon, generate energy in their operation, absorb carbon from the atmosphere, and last much longer than the typical 60-year lifespan of a building (Fig. 1). By combining these strategies, buildings can be designed to go beyond net zero carbon.

The design brings SOM's 2021 high-rise prototype from a visionary concept to a buildable reality. The building would reduce upfront embodied carbon by 70% —from construction alone—when compared to that of a typical high-rise. In the first five years of the tower's life, it would reach a 100% reduction in whole life cycle carbon, achieving net zero. Over an extended, 100-year lifespan, an Urban Sequoia building would absorb more than 300% of the amount of carbon emitted in its construction and operations.

Reduction of upfront carbon emissions for structural and architectural elements is further validated with SOM's in-house EA Tool to demonstrate the effectiveness of employing Urban Sequoia's design strategies, using current technologies. EA Tool is a software developed by SOM to calculate a building's embodied carbon emissions. It enables the architects and engineers to quickly compare the carbon footprint of different structural, curtain wall and MEP systems, as well as base isolation or energy dissipation systems, with the aim to select the optimum design option.

2. Optimised Structural System

The structural system typically accounts for most of the embodied carbon emissions of a high-rise building.



Figure 1. Illustrative Section of the Urban Sequoia Concept Building.

Through optimisation of the building's geometry (Fig. 2), with advanced finite-element analysis techniques, a significant savings in a building's embodied carbon emission can be achieved by reducing structural material quantities. Urban Sequoia utilises a modular system to reduce structural weight. Each module of the floor plate is geometrically optimised to achieve greater structural efficiency, reducing structural floor material by over 50%. The overall shape of the building footprint is also optimised to further reduce wind loads, hence embodied carbon emissions.

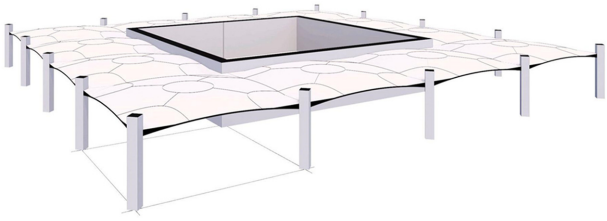


Figure 2. Axonometric Diagram showing Optimised Structural Floor Plate with Thin Shell Profile.

3. Low-carbon Concrete

Low-carbon concrete made with carbon-neutral Portland Cement and other cementitious materials has the potential to be an ecologically friendly material with comparable or superior performance characteristics to traditional Portland Cement and a low carbon footprint (Finke and Leandri, 2020). In Urban Sequoia, low-carbon concrete is used as the main structural material for columns, beams, and walls, with up to 70% cement replacement, which results in a reduction of the structural system's embodied carbon emissions up to 60%.

4. Bio-based Materials

Bio-concrete, hempcrete, timber, and carbon-sequestering fillers, as well as aggregates are examples of materials that absorb and store carbon over their lifetime. Bio-concrete, developed at the University of Colorado Boulder along with Prometheus Materials, is a Living Building Material (LBM), created by combining aggregate, hydro solution, and cyanobacterium. This algae-based, low-carbon concrete alternative primarily uses biological processes to provide a structural binder to any aggregate type (Kologlu et. al, 2022; Sarkisian et. al, 2022).

Hempcrete is a biocomposite material composed of hemp shives (i.e. the woody inner part of the hemp stalk cut into pieces), water, lime and a sand or cement binder. Because this material's strength is limited, it is usually used for non-structural components (Elfordy et. al, 2008; Arrigoni et. al, 2017).

The carbon sequestration of timber-based products happens when the atmospheric CO_2 is sequestered in the photosynthesis of biomass. In exchange, the trees emit oxygen and forever store carbon until they are combusted for fuel or cut to make materials where parts are sent to landfill to decay. Because of their rapid growth, bamboo and other fast-growing plants, such as straw, are regarded among the highest carbon-sequestering materials. For example, Guadua Angustifolia bamboo sequesters as much carbon in 7 years as Douglas fir does in 32 years (Hinkle et. al, 2019).

Urban Sequoia utilises various bio-based materials as part of different building components to reduce the building's overall embodied carbon emissions by up to 40%. For example, low carbon-concrete is used as the



Figure 3. Bio-Based Material Use in the Urban Sequoia Building.

material for the main structure in lieu of traditional Portland Cement concrete. Timber is utilised on flooring and furniture. Bio-cement is used as insulation and in interior partition walls (Fig. 3).

5. Modularised Prefabrication and Construction Approach

Construction-related carbon emissions are substantial - sometimes making up as much as 25% of the total embodied carbon emissions of a building (Sarkisian et. al, 2022). The carbon emitted from construction includes emissions from building machinery, materials transported from various places, and necessary personnel transportation, among other factors.

As a widely used building material, concrete has high embodied carbon emissions, associated with the construction process, in primary relation to the number of days it takes to complete one story in the construction cycle and formwork. Optimising cores and columns (for ease of vertical forming), and floor plate geometry (for ease of horizontal forming) can help reduce floor-to-floor cycles from 7 to 5 days, and even to 3 days (Sarkisian et. al, 2022). One approach to accelerate the construction process involves using prefabrication to achieve fast floor-to-floor construction cycles. While low Portland Cement and low-carbon concrete typically have low early strength, and require extended time to gain higher design strength, precasting can be used to allow the material to reach the necessary strength offsite, and then be quickly erected on-site without any need for formwork. A construction process embraced by these approaches can lead to the pre-assembly of the major building components in order to minimise construction time, waste and all the associated carbon emissions.

Considering this, each module of the Urban Sequoia would be prefabricated and assembled on-site, reducing the construction time by up to 50% and the embodied carbon emissions (associated with construction) by up to 40% (HTA, 2023). The construction downtime and construction carbon footprint related to new interior fit-out can also be significantly reduced in this process. Furthermore, the building is purposely designed such that it can be easily repurposed to accommodate any given

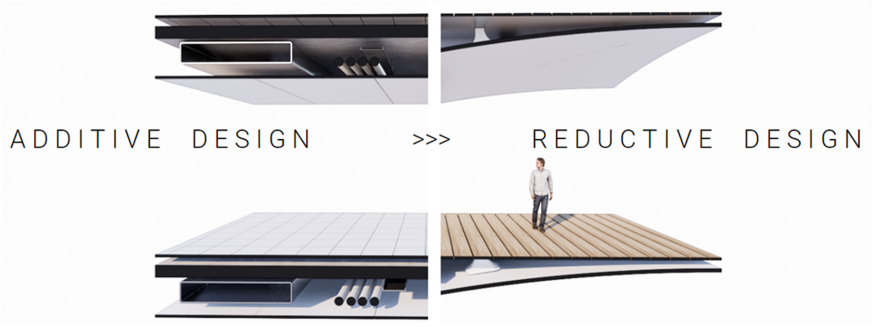


Figure 4. Integrated Floor System Employing a Reductive Design Approach.

function, from hospitality to residential and to commercial, over its entire lifecycle.

6. Holistic Integration of Facade, MEP and Interior Components

Rather than taking the typical, additive construction approach, in which a structure is built, followed by the facade, the MEP and other building systems, as well as the interior fit-out—which all add carbon to the atmosphere—the Urban Sequoia's construction is combined into one, streamlined process. In this reductive approach, every part of the building would serve multiple purposes (Fig. 4). SOM's new approach consolidates and eliminates select building systems that are typically hidden in ceilings, like air ducts and other MEP equipment, significantly decreasing material use.

7. Carbon Capture Technology

Direct Air Capture (DAC) technology captures CO_2 emissions directly from the atmosphere. The captured CO_2 is then transported away, and turned into marketable, industrial and commercial products (Terlouw et. al, 2021).

In the Urban Sequoia building, air flows into ventilation openings, situated on every floor, as well as sky gardens, which double as amenities and provide large air capture zones. Building's natural stack effect then helps move air through the Direct Air Capture machines and absorb CO_2 in the process. The captured carbon would then be stored

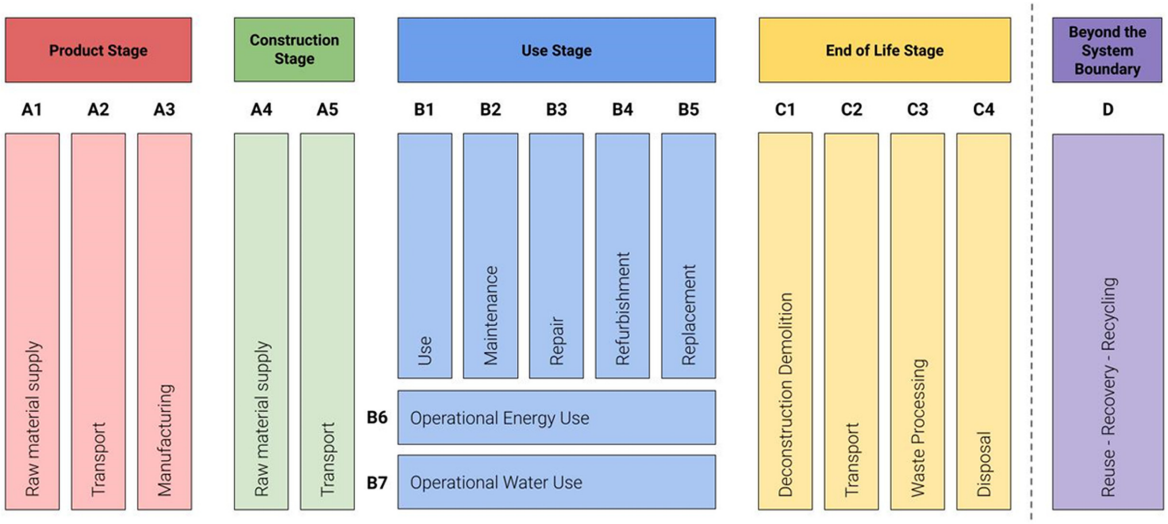


Figure 5. Different Stages of Building Whole Life Cycle Analysis. (according to EN15978)

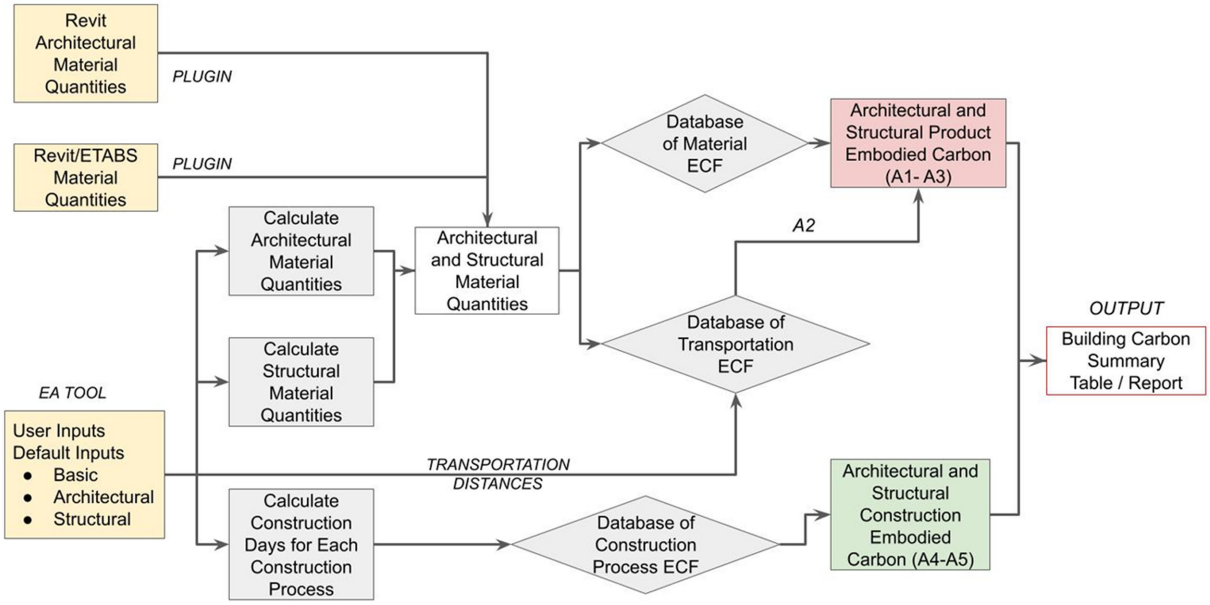


Figure 6. The EA Tool Flowchart for A1 - A5 Carbon Calculation.

and available for use in various industrial applications, completing the carbon cycle and forming the basis of a new carbon-removal economy.

8. EA Tool

The Environmental Analysis Tool (EA Tool) is a software developed by SOM to calculate a building's embodied carbon emissions for different structural, curtain wall, and MEP systems, as well as interior fit-outs, starting from initial, concept designs. The EA Tool provides the user with full flexibility to define various building parameters, including the building material usage, material transportation distances, embodied carbon

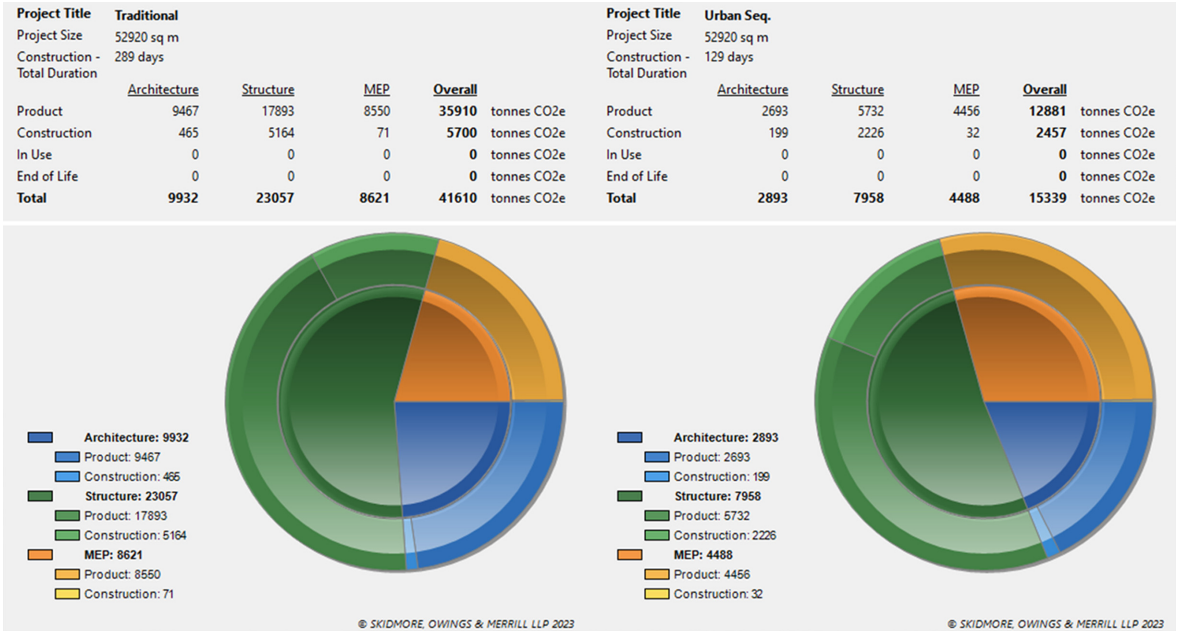


Figure 7. EA Tool User Interface.

Table 1. EA Tool Key Input Parameters

Gross Floor Area (GFA) = 52920 m^2	Traditional Design	Urban Sequoia Design
Unit Superstructure Concrete Quantities (m^3/m^2)	0.446[a]	0.269[a]
Unit Superstructure Rebar Quantities (kg/m^2)	71.38[a]	37.23[a]
Unit Superstructure PT Quantities (kg/m^2)	-	3.17
Unit Foundation Concrete Quantities (m^3/m^2)	0.119[a]	0.095[b]
Unit Foundation Rebar Quantities (kg/m^2)	16.54[a]	13.23[b]
% Superstructure High Strength Concrete	23	23
% Superstructure Medium Strength Concrete	77	77
% Foundation Low Strength Concrete	100	100
High Strength Concrete ECF ($kgCO_2/m^3$)	498[c]	173[d]
Medium Strength Concrete ECF ($kgCO_2/m^3$)	429[c]	152[d]
Low Strength Concrete ECF ($kgCO_2/m^3$)	406[c]	290
Rebar ECF ($kgCO_2/kg$)	0.98[c]	0.56[c]
PT ECF ($kgCO_2/kg$)	-	2.30

Notes:
a. The reduced superstructure material quantities are estimated based on a previous study where both towers are constructed and analysed using a commercial structural analysis software (Sarkisian et. al, 2022).
b. Foundation structural quantities for traditional design is estimated based on a 2.5m-thick mat and a unit reinforcement quantity of $160kg/m^3$. Foundation structural quantities for Urban Sequoia design is estimated based on a 2m-thick mat and a unit reinforcement quantity of $128kg/m^3$, or 80% of traditional design quantities.
c. Material Embodied Carbon Factors (ECFs) are obtained either from industry averages, or actual product specifications (Athena Sustainable Materials Institute, 2021; Carbon Leadership Forum, 2021; One Click LCA, 2022).
d. Concrete material utilises low-carbon concrete with 70% cement replacement.

Table 2. Structural and Architectural A1-A5 Carbon Footprint Comparison

	Total Carbon Footprint (tonnes CO_2)		Unit Carbon Footprint ($kgCO_2/m^2$)	
	Traditional Design	Urban Sequoia Design	Traditional Design	Urban Sequoia Design
Superstructure A1-A3	14,429	3,843	273	73
Foundation A1-A3	3,464	1,889	65	36
Exterior Wall A1-A3	4,208	1,412	80	27
Floor/Ceiling A1-A3	5,259	1,281	99	24
Construction A4-A5	5,629	2,425	106	46
Total	32,989	10,850	623	205
Reduction (%)		67%		67%

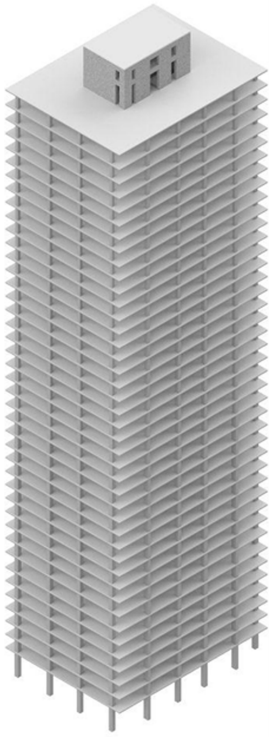


Figure 8. 40-Storey Prototype Building.

factor (ECF) for many common building materials, transportation, and construction process, as well as construction duration. The EA Tool can also directly import material quantities from commercial software, such as Revit and ETABS.

The building's whole life cycle carbon emissions can be divided into four stages, according to the EU standards (BS EN 15978:2011): product, construction, use, and end of life (Fig. 5). The EA Tool has full functionality to accurately compute the upfront embodied carbon emissions (A1 - A5) of a building and gives users the option to manually estimate the use stage, as well as the end of life stage carbon emissions, based on the building's upfront embodied carbon emissions.

The flowchart (Fig. 6) illustrates the EA Tool's upfront embodied carbon emissions' calculation process. The user can either manually input basic building parameters, such as building height, floor areas, structural system, and architectural finishes to estimate the building's material usage, or directly import such quantities from a spreadsheet or a commercial software. Based on these quantities, the program will map the material to a database of material ECFs, to calculate the product stage (A1-A3) embodied carbon emissions. Manual or default transportation distances can be specified to compute the transport-related (A2) embodied carbon emissions, if this term is not already included in the material ECFs. Manual or default construction days for various construction processes can also be specified to determine the carbon emissions related to construction stage (A4-A5).

9. EA Tool Verification

The effectiveness of employing Urban Sequoia's design strategies to reduce a building's whole life cycle carbon emissions is validated using the EA Tool (Fig. 7). In the following studies, the architectural and structural A1-A5 embodied carbon emissions of a 40-storey prototype building is assessed - comparing an Urban Sequoia building to a traditional reinforced concrete structure built with Portland Cement.

The structural system for the prototype tower includes a reinforced concrete core-only lateral load-resisting system and reinforced concrete perimeter gravity columns. A 3D representation of the building is shown (Fig. 8). In the traditional design approach, a conventional reinforced concrete floor plate is used. All concrete elements utilise traditional Portland Cement. In the Urban Sequoia Design approach, the floor plate is geometrically optimised with with a shell structure, balanced by post-tensioned (PT) tendons. Low-carbon concrete is also used throughout as the main structural material. The architectural material ECFs in the Urban Sequoia design is also generally lower compared to that of the traditional design due to its use of bio-based materials.

Table 1 summarises the key inputs utilised for the EA Tool. The main differences between an Urban Sequoia building and a traditional design include lower structural



Figure 9. Urban Sequoia at City Scale.

material quantities (due to structural design optimisation), lower material embodied carbon factors (due to low carbon concrete), and a bio-based (wood) facade system (instead of a commonly used aluminium one).

Table 2 summarises the key outputs of the EA Tool. It is evident that the Urban Sequoia design approach can reduce the structural and architectural embodied carbon emissions (in Modules A1-A5) by 67%, when compared to a similar building designed using traditional, additive approaches.

10. Conclusion

Urban Sequoia is a buildable and validated concept that can transform the current built-environment, at both building and city scales, to a truly resilient and carbon absorbing 'urban forest' (Fig. 9). Using reductive and integrated design approaches, modular construction techniques, and sustainable, low-carbon materials, together with high performance building systems, new buildings can start off with only 10% of the whole life cycle carbon emissions, compared to that of a business-as-usual building. With the addition of direct air capture units, buildings can continuously absorb carbon from the atmosphere, like that of a tree, reducing their their whole life cycle carbon emissions by 340% over their 100–year life cycle.

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