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Towards the Carbon-Neutral High-Rise: The Role of Embodied Carbon

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Abstract

The built environment sector is responsible for some 39 percent of global carbon emissions. Therefore, decarbonizing the building industry is one of the most effective and important actions on the climate change-mitigation agenda. High-rise buildings produce carbon emissions throughout their life cycles. Traditionally, attention has mainly been given to their operational carbon footprint. However, embodied carbon of built assets contributes to around 11 percent of global carbon emissions, and will be responsible for approximately 50 percent of the entire carbon footprint of new construction between now and 2050.

This paper presents a case study on how the optimization of various structural concrete elements of towers could contribute towards significant carbon savings. For example, by optimizing the design of core walls, slabs, and raft foundations, the authors have managed to achieve a carbon reduction equivalent to the emissions that would result from 78 million kilometers (14 million kgCO$_2$e) of travel in an average gasoline-powered car. The paper then summarizes a set of tangible savings made via various design optimization techniques.

Keywords: Carbon Neutrality, Embodied Carbon, Skyscraper, Sustainability

The Climate Emergency

Greenhouse gas (GHG) emissions have risen at a rate of 1.5 percent per year in the last decade, stabilizing only briefly between 2014 and 2016. The total GHG emissions reached a record high of 55.3 gigatons of carbon-dioxide equivalent (GtCO$_2$e) in 2018. Implementing the current policies, GHG emissions are estimated to reach 60 GtCO$_2$e by 2030. However, to meet the Paris Agreement goals for 2030, the current emissions must be lowered by 30 GtCO$_2$e, and only then will global warming be limited to less than 1.5°C (UNEP 2019). The damage from climate change will be widespread, and sometimes surprising. It will go far beyond drought, melting ice sheets, and causing crop failures. The risks that weather and climate pose to human life are not always as specific to the peculiar circumstances of time and place—consider the sudden and global onset of the COVID-19 epidemic (Declan 2020). Figure 1 (Houghton et al. 2001) shows the increases in both the mean, and the variability of climate events, which affects the probability of hot and cold extremes, leading to more frequent hot events with more extreme high temperatures, and fewer cold events.

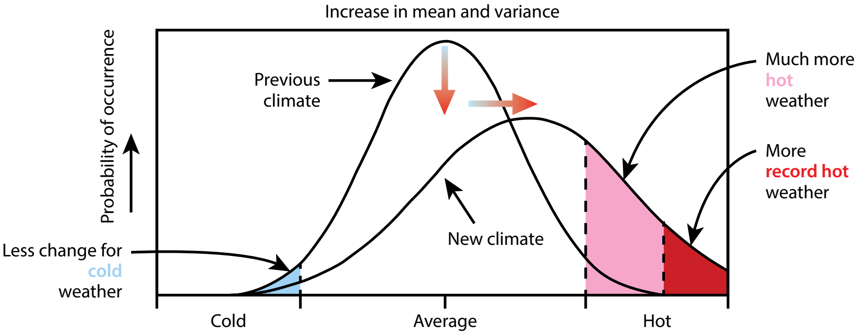


Figure 1. Extreme climate events are likely to increase, both in terms of probability and severity, if the planet continues to warm at current rates. Source: Houghton et al. 2001

Lessons learned from the COVID-19 pandemic show that we cannot ignore the warnings that are repeatedly issued by the scientific community and be caught unprepared for another natural disaster. Currently, there is a strong consensus amongst scientists that climate change will be the next global crisis that we will face

(IPCC 2018, UN DESA 2019), from which no one will be able to self-isolate, and which now requires immediate mitigative actions from every sector and industry.

Role of The Built Environment Sector

The building sector has a crucial role to play in the response to the global warming crisis. This sector alone is responsible for 39 percent of global carbon emissions (UNEP & IEA 2017). Thus, decarbonization of buildings is a high priority for all stakeholders in this industry, to enable them to meet the vision set out by the World Green Building Council (WGBC) in the report *Bringing Embodied Carbon Upfront* (WorldGBC 2019).

Operational Versus Embodied Carbon

A building's carbon footprint is addressed on two fronts—operational carbon and embodied carbon. Operational carbon commonly refers to the emissions associated with energy used to operate the building. To achieve operational carbon reduction, the carbon cost of the building itself may increase, as the building will require additional materials, such as use of insulation and triple-glazed glass façades for the building envelope (Drew & Quintanilla 2017). The embodied carbon includes the energy use and carbon emissions resulting from the production of building and construction materials. At the building design level, embodied carbon reductions result in cost savings to the project, as demonstrated in the case study hence. Optimizations in design must occur from project inception, and the accuracy of assessment increases as the project design progresses. The WGBC has set out a vision that by 2030, all new buildings, infrastructure, and renovations should have at least 40 percent less embodied carbon, with significant upfront carbon reduction, and all new buildings must be net-zero operational carbon. By 2050, new buildings, infrastructure, and renovations are to not only have net-zero embodied carbon—all buildings, including existing buildings, must be net-zero operational carbon (WorldGBC 2019).

> “The amount of carbon savings due to replacement of the cement content within the raft concrete is equal to 5,757 metric tons of CO_2e, which is almost 40 times bigger than the transport carbon.”

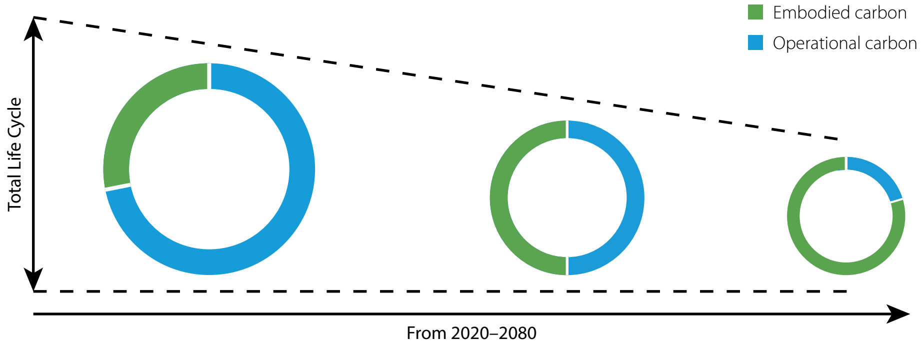


Figure 2. The proportional impact of embodied carbon associated with the built environment is expected to increase over the coming decades. Source: World Green Building Council

Operational carbon accounts for 28 percent, while embodied carbon accounts for 11 percent of the carbon impact from the building sector. Traditionally, attention has been largely focused on the reduction of operational carbon. However, the WGBC predicts that if it is not controlled now, then by 2050, 50 percent of the emissions will come from embodied carbon. Figure 2 depicts the increasing significance of embodied carbon, as operational carbon significantly reduces due to technological innovation and renewable offsets. Therefore, it is important to manage embodied carbon right from a project's inception.

Life Cycle Stages of a Building

The standard EN 15978 defines the life cycle stages of a building in the following terms: the product stage (A1–3); the construction process stage (A4–5); the use stage (B1–7); the end-of-life stage (C1–4); and the beyond-the-building-life-cycle stage (D) (see Figure 3) (BSI 2011). The stages B6 and B7 are the operational carbon stages. The embodied carbon consists of carbon emissions associated with materials and construction processes throughout the whole life cycle of a building or piece of infrastructure.

Upfront carbon comprises the emissions caused in the material production and construction phases of the life cycle before the building or infrastructure begins to be used. Recently, there has been an increased emphasis on upfront carbon, as opposed to life cycle assessment (LCA), as LCA might not truly reflect the urgency of today's impacts, and the fact that we need to reduce the embodied carbon now. Therefore, extra attention is given to the A1–A3 stages, and upon availability of data, the upfront assessment is extended to A4–A5 stages too. However, we cannot address one without the other; urgent action must be taken to tackle upfront carbon while designing with the whole-life carbon impact in mind.

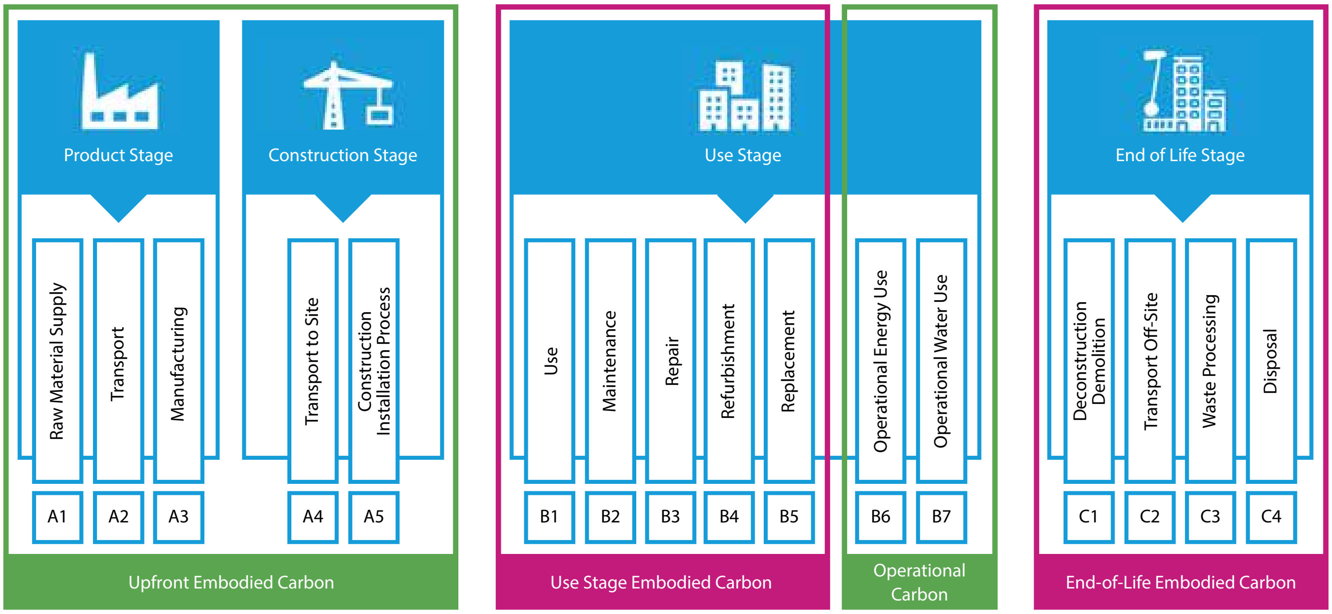


Figure 3. Life cycle stages of a building, per EN 15978. The focus of this paper is on the embodied carbon stages, particularly stages A1–A3, "upfront embodied carbon." Source: BSI

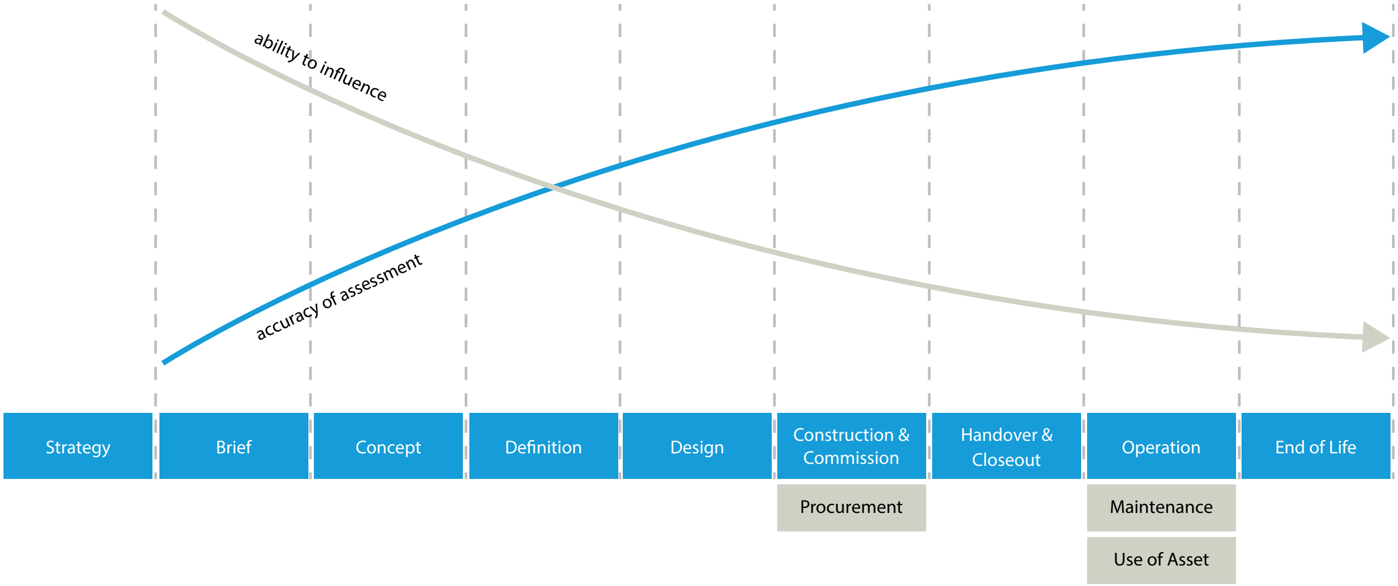


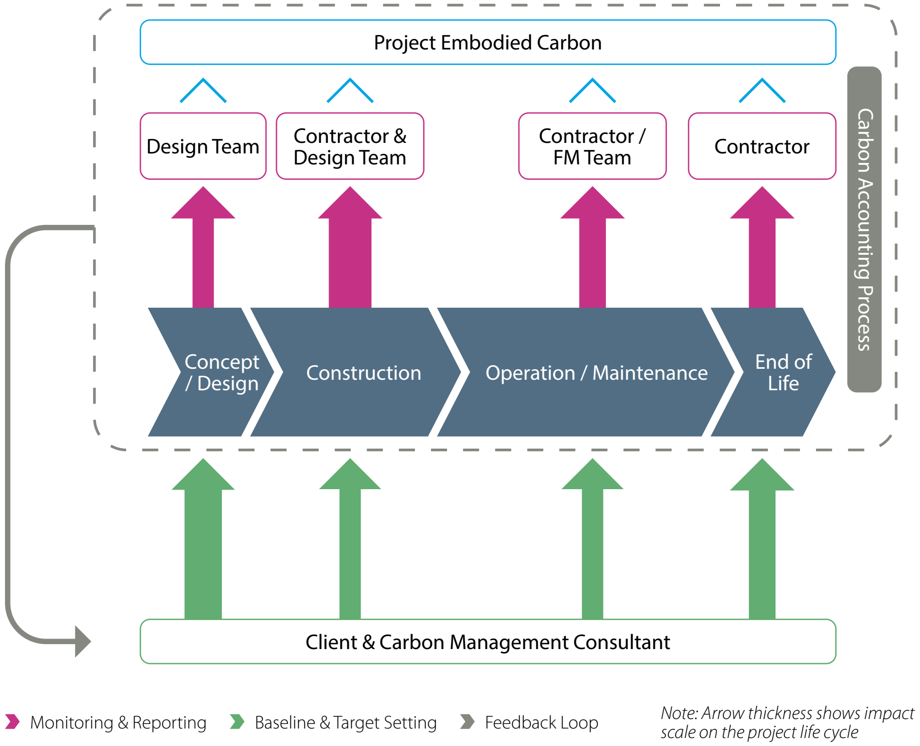
Figure 4. The further a construction project progresses into the design stages, the less influence the design team will have on reducing the embodied carbon. Source: Manidaki et al. 2016

Carbon Management Process

A carbon management process firstly enables the client and design team to review the impact of the building design and understand the main contributors towards the embodied carbon on the project. It also provides the project team with an opportunity to constantly review and assess the design, and be able to suggest and make improvements throughout the project life cycle to influence its embodied carbon. It is important to note that the further the project progresses into the design stages, the less influence the design team will have on reducing the embodied carbon (see Figure 4) (Manidaki et al. 2016).

The carbon management process begins with defining the targets and baseline together with the client during the concept/planning stage. A series of workshops should be held between the client and carbon management consultant to set reasonable key performance indicators (KPIs) and set up tracking/reporting tools.

"Carbon accounting" is the stage in the carbon management process where strategies recommended by the design team are validated with quantifiable facts. The key features of the process are shown in Figure 5. To reduce the embodied footprint of our buildings, it is essential to integrate the carbon management processes into the development of all the built environment sectors and disciplines. Carbon accounting enables development managers to make informed decisions towards achieving significant carbon reductions and challenging the status quo.



Note: Arrow thickness shows impact scale on the project life cycle

Figure 5. The key features of the carbon accounting process, in which strategies recommended by the design team are validated with quantifiable facts. Source: Connaughton, Weight & Jones 2013

The following are generally considered to be major materials and components that could influence the overall embodied carbon in a high-rise building: concrete/steel structures, bricks, metals, timber, glazing and finishes (Connaughton, Weight & Jones 2013).

This paper focuses on stages A1 to A3 of the upfront embodied carbon life cycle stages seen in Figure 3, and by means of a case study, demonstrates significant savings that can be achieved simply from optimization of various structural concrete elements. The savings are calculated based on the Inventory of Carbon & Energy (ICE) V3.0 carbon conversion factors (Hammond & Jones 2019).

Case Study: Pixel, Makers District (Seven Towers)

The Makers District site is located in Abu Dhabi on the northeast side of Reem Island within Shams Abu Dhabi, facing Saadiyat Island. The master plan development is estimated to have a gross floor area (GFA) of around 730,000 square meters, sitting within a site area of approximately 176,600 square meters.

Figure 6. Rendering of the Pixel project in Abu Dhabi, consisting of seven towers of varying height. It is a mixed-use residential development with retail, offices, and live/work/makers/art spaces. © MVRDV

Within this Makers District master plan, the architecture firm MVRDV provided a fascinating design for the "Pixel" towers and worked together with the authors to deliver these iconic buildings. The Pixel plot is a mixed-use residential development with retail, offices, and live/work/maker/art spaces. The design consists of seven towers, which progressively increase in height from the east to the west of the site. Taking visual inspiration from marble quarries, each tower is fragmented such that "pixelated" cuboid masses are subtracted from the higher parts of the towers, and give the effect of being added to the lower parts of the towers. This allows for a more human scale at the ground level, creating a variety of differently-sized spaces for retail, restaurants, and creative interaction. Figure 6 is a visualization of the Pixel project (MVRDV 2017).

The Pixel towers are classified as mid-to-high-rise structures, all of different configurations. Although there are aspects of commonality and some repetition within individual towers, and between towers—the unique configuration of each tower means that each structural configuration and design must be individually developed, while still taking advantage of the available commonality and repetition where possible.

The main aspects of the buildings' configurations that are specific or unique to each building include the different heights (ranging from G+8 to G+20); the multiple floor-plate configurations within each building and between buildings; and the unique arrangement of three-dimensional cut-backs at the upper levels. Primary perimeter columns are removed at some levels, and parts of the typical floor plates are removed. Moreover, each building has discontinuities in internal columns, resulting either in the need for transfer structures, blade columns of varying shapes, hanging columns, or longer-span floor plates. Figure 7 shows the primary structure of the project.

Since the project inception, the structural team continually optimized the design of various structural concrete elements. This has resulted in major embodied carbon savings in each tower, by adopting the following design strategies.

The tower slab compositions were changed from reinforced concrete to post-tensioned slabs, reducing the volume of concrete by 8 percent. Table 1 shows the volume of savings per tower; the resulting savings on

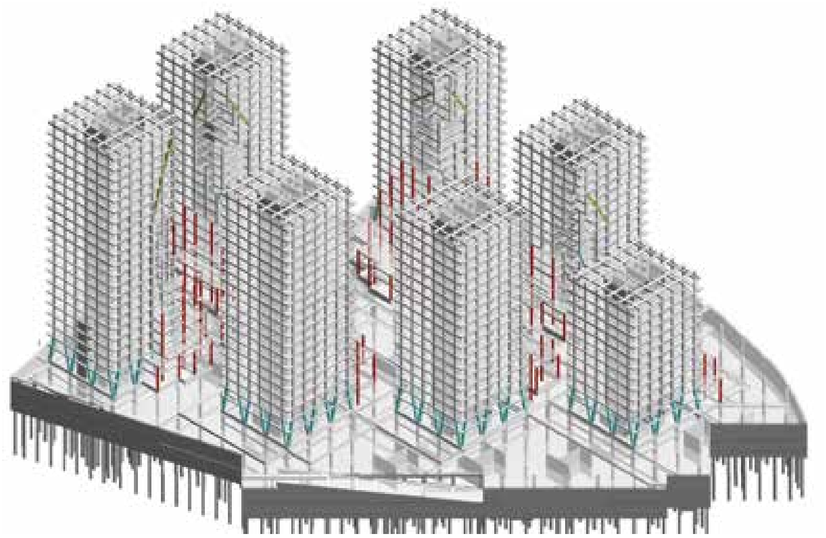


Figure 7. The primary structural system of the Pixel project, Abu Dhabi. Each building has discontinuities in internal columns, resulting either in the need for transfer structures, blade columns of varying shapes, hanging columns, or longer-span floor plates. © Ramboll Group

Towers	No. of Floors Above L0	Grade (GGBS Content)	Volume of Concrete	
			Post-Tensioned Slab	Reinforced Concrete
T1	12	C50 (30%)	1,832 m^3	2,008 m^3
T2	18	C50 (30%)	2,817 m^3	3,084 m^3
T3	20	C50 (30%)	3,031 m^3	3,347 m^3
T4	22	C50 (30%)	3,475 m^3	3,774 m^3
T5	18	C50 (30%)	2,896 m^3	3,137 m^3
T6	16	C50 (30%)	2,729 m^3	2,931 m^3
T7	14	C50 (30%)	2,078 m^3	2,314 m^3
		Total	**18,857** m^3	**20,594** m^3
		Savings in Volume of Concrete	**1,737** m^3	

Table 1. Savings in the volume of concrete used after the choice was made to switch to post-tensioned slabs over reinforced concrete slabs. © Ramboll Group

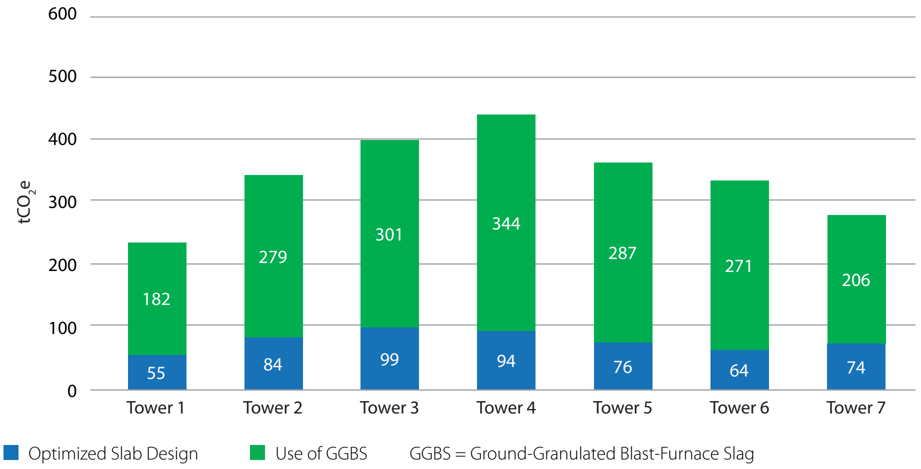


Figure 8. Amount of carbon-dioxide equivalent saved by choosing the post-tensioned slab design over reinforced concrete, expressed in metric tons. © Ramboll Group

embodied carbon are then presented in Figure 8.

Another focus of design optimization was on vertical elements of the structure, where the sizes of the perimeter columns have been reduced, along with reduction in the concrete grade for the higher floors. Table 2 shows scenario 1, which was the initial concept design, compared to scenario 2 with the optimized dimensions of vertical elements.

The resulted savings on embodied carbon are then presented in Figure 9.

As previously seen in Figure 7, a number of V-shaped columns have been provided between Level 0 and Level 2. This has allowed the elimination of transfer beams at Level 2 for all seven towers. In addition, by extending the slab edge and designing a flat slab, the perimeter beams were also eliminated. Table 3 and Figure 10 show the savings resulting from the reduction of these beams.

It is worth noting that, due to the predetermined architectural layouts of Towers 5 and 6, significant modification of layouts was not possible, and therefore elimination of edge beams could not be achieved for these two towers, which would otherwise have resulted in further savings.

Lastly, the Basement 2 (raft), Basement 1, mezzanine, and podium slabs have been optimized to use varying quantities of cement replacement. Figure 11 presents the carbon savings achieved by using cement replacement in these levels.

One of the major cement components, ground-granulated blast-furnace slag (GGBS), a glassy powder obtained by quenching molten iron slag from the steelmaking process with water, is not widely available in the Middle East, and has to be shipped from abroad, resulting in extra transport-related carbon emissions. To appraise the impact of transport carbon of GGBS to the region, a sensitivity-analysis exercise was carried out. It has been

Towers	**Level Description**	**Concrete Grade (GGBS Content)**		**Volume of Concrete**	
		Scenario 1	**Scenario 2**	**Scenario 1**	**Scenario 2**
T1	B2 to L4	C60 (30%)	C60 (30%)	997 m³	966 m³
	L5 to L12	C60 (30%)	C50 (30%)	979 m³	855 m³
T2	B2 to L9	C60 (30%)	C60 (30%)	1,629 m³	1,546 m³
	L10 to L18	C60 (30%)	C50 (30%)	1,109 m³	932 m³
T3	B2 to L9	C60 (30%)	C60 (30%)	1,692 m³	1,609 m³
	L10 to L20	C60 (30%)	C50 (30%)	1,353 m³	1,156 m³
T4	B2 to L9	C60 (30%)	C60 (30%)	1,748 m³	1,680 m³
	L10 to L22	C60 (30%)	C50 (30%)	1,656 m³	1,449 m³
T5	B2 to L9	C60 (30%)	C60 (30%)	1,629 m³	1,546 m³
	L10 to L18	C60 (30%)	C50 (30%)	1,109 m³	953 m³
T6	B2 to L4	C60 (30%)	C60 (30%)	1,001 m³	970 m³
	L5 to L16	C60 (30%)	C50 (30%)	1,485 m³	1,319 m³
T7	B2 to L4	C60 (30%)	C60 (30%)	1,001 m³	970 m³
	L5 to L14	C60 (30%)	C50 (30%)	1,234 m³	1,068 m³
			Total	**18,662** m³	**17,019** m³

Table 2. Comparison of the reduction in volume of concrete due to reduction in the size of perimeter columns throughout the Pixel project. Scenario 1 = initial concept design; Scenario 2 = optimized, reduced dimensions of vertical elements. © Ramboll Group

Optimization	**Towers – Floor**	**Grade (GGBS Content)**	**Savings in Vol. of Concrete**
Elimination of transfer beams	All—L2	C50 (30%)	884 m³
Elimination of perimeter beams	T1 – L3 to L10 T2 – L3 to L16 T3 – L3 to L18 T4 – L3 to L20 T7 – L3 to L12	C50 (30%)	1,041 m³
		Total Savings	**1,925** m³

Table 3. Savings achieved in terms of concrete volume, resulting from the elimination of certain transfer and perimeter beams in the Pixel project. © Ramboll Group

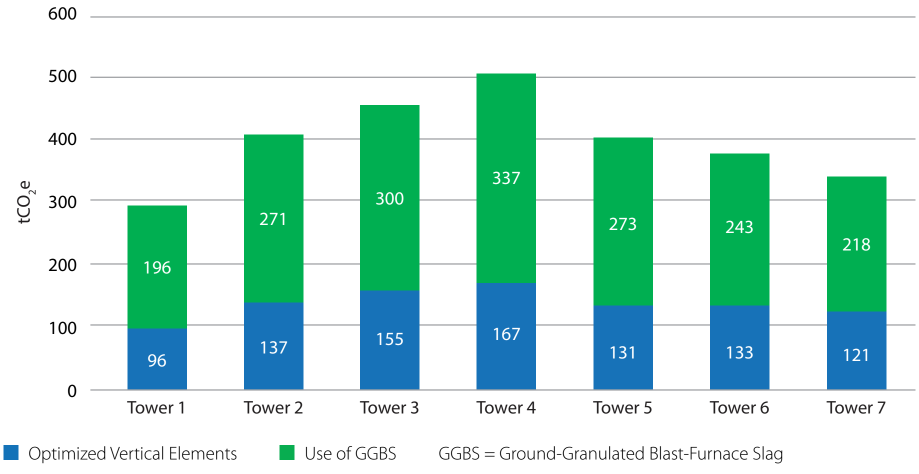


Figure 9. Amount of carbon-dioxide equivalent saved by choosing smaller-dimensioned vertical elements, expressed in metric tons. © Ramboll Group

> “Based on a representative market rate for concrete in the UAE, the project estimates savings of approximately US$4.9 million.”

assumed that if GGBS is transported from a port in Europe to the Jebel Ali port in Dubai (e.g., 10,000 kilometers of sea freight) the carbon conversion factor of 0.00354 $\text{kgCO}_2\text{e/t.km}$ should be applied. (This assumes an average bulk carrier using carbon conversion factors from the UK Government’s GHG Conversion Factors for Company Reporting).

The total GGBS quantity needed for the raft of this project was estimated to be at around 4,188 metric tons. Therefore, the transport carbon emission of this amount of GGBS could be calculated as seen here:

$$10{,}000\ km \times 4{,}188\ t \times 0.00354\ kgCO_2e/t.km = 148\ tCO_2e$$

The amount of carbon savings due to replacement of the cement content within the raft concrete is equal to 5,757 metric tons of CO_2e, which is almost 40 times bigger than the transport carbon. Therefore, it is beneficial to import such low-carbon material via the lowest-carbon transport options available, such as sea freight, to achieve an overall embodied carbon savings.

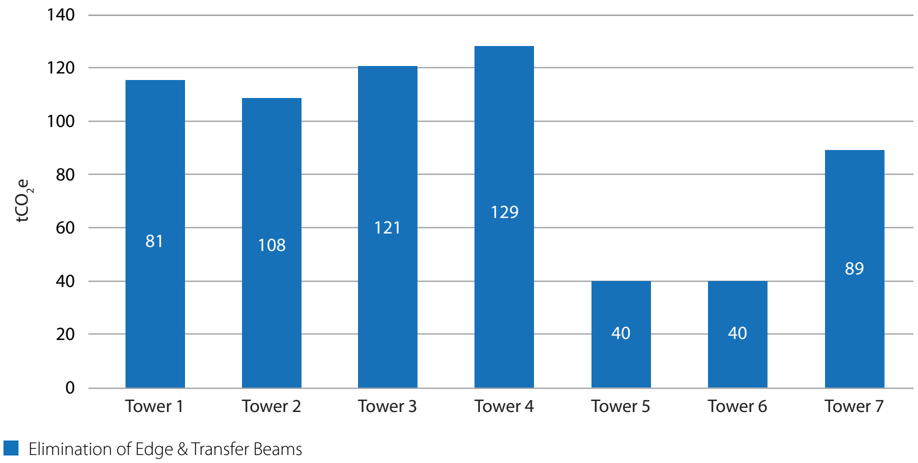
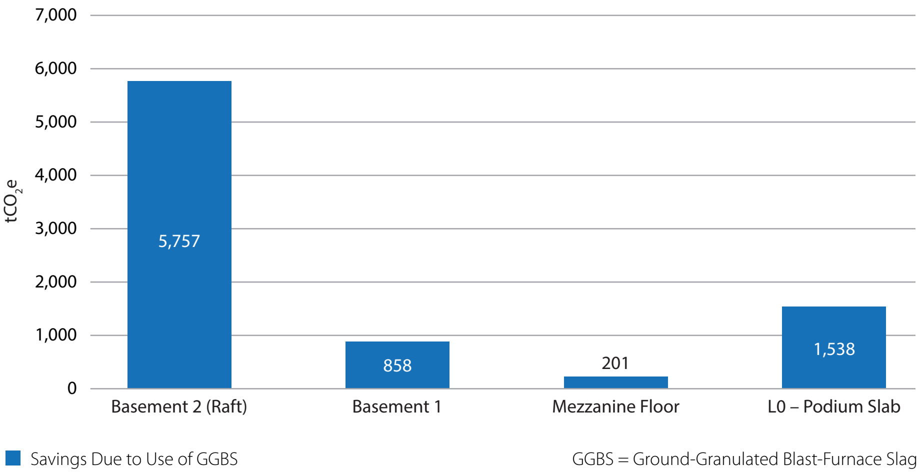


Figure 10. Amount of carbon-dioxide equivalent saved by eliminating edge and transfer beams in the Pixel project, expressed in metric tons. © Ramboll Group



GGBS = Ground-Granulated Blast-Furnace Slag

Figure 11. Consolidated carbon-dioxide equivalent savings due to use of GGBS in basement, mezzanine, and podium slab floors of the Pixel project. © Ramboll Group

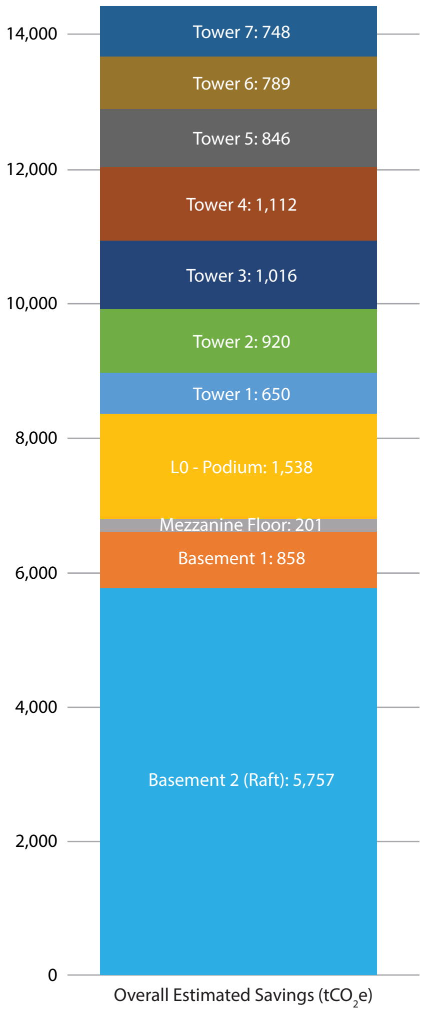


Figure 12. Overall estimated savings in terms of metric tons of carbon-dioxide equivalent, based on all optimizations described in the paper. © Ramboll Group

The total embodied carbon savings achieved through various design optimization measures is equal to 14,435 tCO_2e, i.e., a 37 percent savings when comparing like-with-like components (see Figure 12). To put that in context, this amount of CO_2e savings is equivalent to 78 million kilometers of travel in an average gasoline-powered car (using carbon conversion factor from UK Government GHG Conversion Factors for Company Reporting). Figure 13 demonstrates the percentage contributions the following structural optimizations used in the Pixel case study: slab volume reduction, vertical element optimizations, elimination of typical level beams, and use of GGBS in the superstructure and substructure.

Lowering embodied carbon is mainly achieved by optimizing the design and achieving savings on material consumption; it is therefore a beneficial exercise to all stakeholders, including clients, as it will result in value engineering outcomes and cost savings. The earlier the consideration and planning for lowering embodied carbon in the design stage, the greater the savings. Based on a representative market rate for concrete in the UAE, the project estimates savings of approximately US$4.9 million.

Conclusion

There seems to be limited data on various embodied carbon benchmarks that are consistent and verifiable. Developing a reliable benchmark for various typologies of high-rise buildings should be the subject of further research. This would enable designers to evaluate the carbon footprint of their design against these benchmarks and achieve further savings towards the net-zero carbon aspiration. ■

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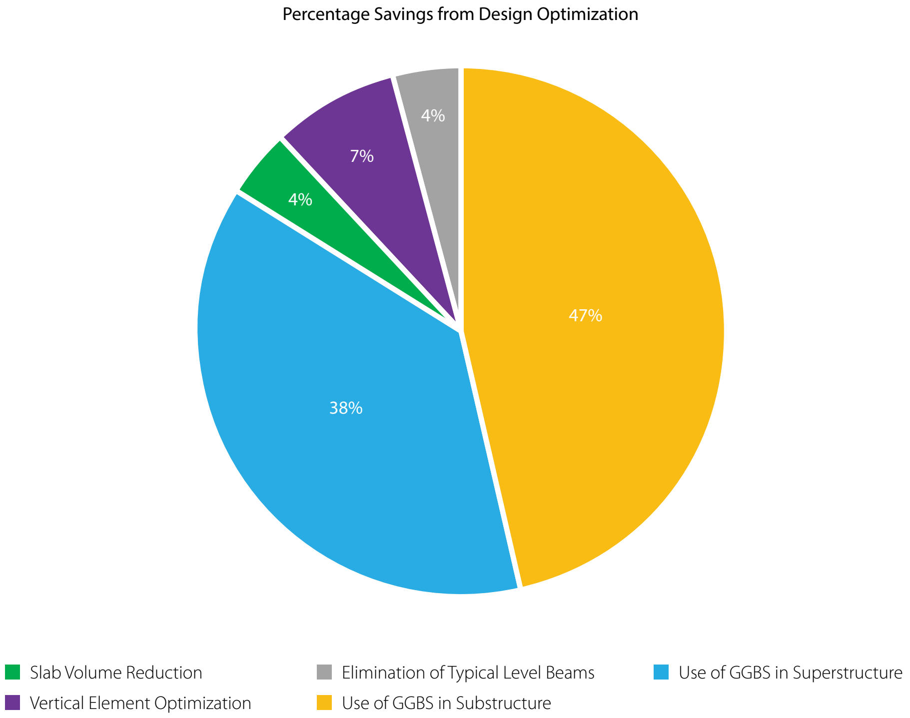

Figure 13. Overall estimated savings in terms of metric tons of carbon-dioxide equivalent: percentage attributable to each optimization described in the paper. © Ramboll Group

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