Sustainability In Construction Project Minimizing Environmental Impact of Cement and Concrete

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Abstract – The construction sector faces increasing pressure to curtail embodied carbon associated with cement and concrete. This study quantifies the baseline embodied CO_2 emissions of a multi-storey commercial building and evaluates the reduction achieved through structural optimization. A Building Information Modeling (BIM) workflow provided accurate quantity take-off, which was coupled with Life Cycle Assessment (LCA) across stages. In the baseline design, total concrete volume was 510.038 m^3 with associated emissions of 166,100 kg CO_2 (including transport). The optimized design reduced concrete volume to 435.738 m^3 and total emissions to 141,904 kg CO_2, a 14.57% reduction, primarily from resizing slabs, beams, and columns while maintaining code compliance and structural integrity. The work demonstrates a practical, replicable pathway for integrating BIM–LCA in early-stage design to deliver tangible carbon savings in resource-constrained contexts.

Keywords- Carbon Emission, Building Information Modelling BIM, Life Cycle Assessment LCA, Structural optimization, Sustainable construction

I. INTRODUCTION

Cement and concrete are indispensable to modern construction yet contribute substantially to global greenhouse gas emissions, resource consumption, and ecological degradation. Decarbonization efforts increasingly focus on both material innovations such as clinker reduction via supplementary cementitious materials (SCMs) and demand-side strategies that optimize structural systems and reduce Concrete volume. Alongside materials and design, digital tools like Building Information Modeling (BIM) and Life Cycle Assessment (LCA) can reveal carbon hotspots and support iterative design decisions that lower embodied impacts early in projects.

Beyond production, the environmental burden of concrete is shaped by mix design, material sourcing, and structural efficiency, all of which influence embodied energy and carbon throughout a project's life cycle. (Purnell & Black, 2012; Wałach, 2020) Research demonstrates that optimizing mix proportions and incorporating supplementary cementitious materials (SCMs) can significantly lower emissions without compromising performance, while life-cycle assessment (LCA) offers a robust framework for quantifying and mitigating impacts from cradle to grave. (Kim et al., 2013; Proske et al., 2014; Heede & Belie, 2012; Ortiz et al., 2009)

Recent advances emphasize eco-efficiency through strategies such as recycled aggregates, alternative binders (including nanocement), and process innovations that reduce both carbon intensity and material waste. (Dunuweera & Rajapakse, 2018; Naik & Moriconi, 2005) In parallel, digital tools particularly Building Information Modeling (BIM) and design optimization techniques are increasingly employed to enhance material efficiency, cut embodied energy, and streamline decision-making across project stages. (Choi et al., 2017; Lu et al., 2017)

Despite these developments, rapid urbanization and escalating infrastructure demand continue to intensify environmental pressures, revealing persistent barriers to mainstream adoption of low-carbon practices, including cost concerns, technical constraints, and limited stakeholder awareness. (Mohamad et al., 2021; Makul, 2020; Proske et al., 2014; Dunuweera & Rajapakse, 2018) Conventional design cultures that prioritize structural performance over environmental outcomes further exacerbate inefficient material use and emissions. (Laníková et al., 2014; Medeiros & Kripka, 2014) Consequently, a holistic approach that integrates materials innovation, LCA, sustainable design principles, and supportive policy mechanisms is essential to align the sector with climate-mitigation goals. (Habert et al., 2020; Ortiz et al., 2009

II. LITERATURE REVIEW

Sustainability in cement and concrete has evolved from a narrow emphasis on durability and material efficiency to a comprehensive life-cycle perspective that addresses greenhouse-gas emissions, energy intensity, resource depletion, and design optimization across the built environment (Ali et al., 2011; Habert et al., 2020; Ortiz et al., 2009). Cement production is consistently identified as a major global CO_2 source because of limestone calcination and high thermal energy demand, while concrete's embodied impacts vary with mix design, structural requirements, logistics, and service life (Ali et al., 2011; Habert et al., 2020; Purnell & Black, 2012).

Historically, cementitious systems trace back to ancient lime–pozzolan binders, but the nineteenth-century advent of Portland cement enabled mass standardization and the rapid expansion of bridges, highways, and high-rise structures (Glavind, 2009; Mehta, 1999). Concrete's versatility, strength, and durability made it the backbone of modern infrastructure, yet this ubiquity amplifies environmental burdens and sharpens the imperative for low-carbon practices (Mehta, 2001; Naik, 2008).

Global production now exceeds 4 billion metric tons of cement annually, with demand concentrated in rapidly urbanizing regions; correspondingly, concrete consumption surpasses 30 billion tons per year (Habert et al., 2020; Makul, 2020). Cement manufacture contributes an estimated 5–8% of anthropogenic CO_2, while many developed economies are pushing clinker substitution and low-carbon technologies even as Asia—particularly China and India—dominates output (Ali et al., 2011; Mohamad et al., 2021; Ortiz et al., 2009).

Cement's environmental profile arises from raw-material extraction (land degradation, biodiversity loss, dust, and water use), kiln energy intensity (>1,400 °C), and stack emissions (CO_2, NO_x, SO_x, particulates) (Ali et al., 2011; Salas et al., 2016). Concrete's footprint spans the full life cycle—from extraction and manufacturing to transport, construction, maintenance, and end-of-life—making early design choices (e.g., strength class, cross-section sizing, paste volume) pivotal levers for reducing embodied carbon (Heede & De Belie, 2012; Ortiz et al., 2009; Tae et al., 2011). Logistics also matter: long-haul transport of cement and aggregates can materially increase emissions, strengthening the case for local sourcing and on-site batching where feasible (Proske et al., 2014; Wałach, 2020; Yun & Wu, 2015).

Decarbonization strategies consistently emphasized include reducing clinker factor with supplementary cementitious materials, upgrading kiln/plant energy efficiency, optimizing mixes to minimize paste, using high-strength concretes where they reduce total material, and integrating Building Information Modeling with life-cycle assessment for early-stage, low-carbon decisions (Damineli et al., 2010; Habert et al., 2020; Najjar et al., 2017; Soust-Verdaguer et al., 2017). Circular approaches—recycled aggregates and industrial by-products (e.g., fly ash, slag, silica fume)—lower virgin-material demand and divert waste, while nanotechnology and advanced admixtures enable strength and durability gains that translate into life-cycle savings (Naik & Moriconi, 2005; Dunuweera & Rajapakse, 2018; Abbas et al., 2016; Suhendro, 2014). Digital tools (BIM-LCA workflows) enhance quantity take-offs, scenario testing, and coordination, supporting consistent reductions in embodied energy and CO_2 (Chong et al., 2017; Lu et al., 2017; Shadram et al., 2016; Wong & Zhou, 2015).

Empirical studies link binder content and strength class to building-scale emissions, showing that rationalized structural systems and sustainable constituents can deliver measurable impact reductions without compromising performance; climate context and transport logistics further shape outcomes, reinforcing the value of localized LCA during concept design (Chamasemani et al., 2023; Mostafaei et al., 2023; Purnell & Black, 2012; Wong & Zhou, 2015). Remaining gaps include limited localized evidence in rapidly urbanizing regions, uncertainties around cost and scalability of low-carbon solutions, and the need for stronger policy instruments and collaboration to accelerate adoption (Adesina, 2020; Habert et al., 2020; Makul, 2020; Proske et al., 2014)

III. MATERIALS AND METHODS

This study employed a quantitative, case-based experimental design with a life-cycle assessment (LCA) system boundary spanning material production,transport, and construction, and computed emissions as the product of material quantities and corresponding emission factors. BIM models supported quantity take-off by extracting volumes for slabs, beams, columns, and foundations for both the baseline and optimized designs. The analysis assumed Concrete Grade C20 with a nominal mix proportion of 1:1.5:3, and applied a transport factor for a 33-ton articulated truck to model cement freight from Ibese to Ibadan (97.2 miles). For comparative calculations, an emission factor of 320 kg CO_2 per m^3 of placed concrete was used, while transport emissions were estimated using tonne·km factors combined with route-specific trip distances.

IV. RESULTS

Structural optimization produced measurable reductions in concrete volume and associated CO_2 emissions. Key outcomes for baseline and optimized scenarios are summarized in Tables below

Table 1. Baseline concrete extraction summary by storey and element (m^3)

Storey	Column	Beam	Slab	Foundation	Total
Foundation	2.359	39.132	34.759	112.671	188.922
1	15.243	21.104	34.844	0	71.192
2	15.243	21.104	34.844	0	71.192
3	15.243	21.104	34.844	0	71.192
4	15.243	21.104	34.844	0	71.192
5	15.243	21.104	0	0	36.348
TOTAL	78.576	144.653	174.137	112.671	510.038

Table 2. Baseline CO_2 Emission Generate on Concrete Per Story

Storey	Column (m^3)	Beam (m^3)	Slab (m^3)	Foundation (m^3)	Total (m^3)	CO_2 Emission kg/m^3
Foundation	2.359	39.132	34.759	112.671	188.922	60,455.04
1	15.243	21.104	34.844	0	71.192	22,781.44
2	15.243	21.104	34.844	0	71.192	22,781.44
3	15.243	21.104	34.844	0	71.192	22,781.44
4	15.243	21.104	34.844	0	71.192	22,781.44
5	15.243	21.104	0	0	36.348	11,631.36
TOTAL	78.576	144.653	174.137	112.671	510.038	163,212.16

4.2 Baseline Cement Transport Analysis

For the baseline structural members, Concrete Grade C20 was adopted with a nominal mix ratio of 1: 1.5: 3 (cement: fine aggregate: coarse aggregate). Table 4.3 shows the baseline CO_2 emission generated during transportation of cement per storey while table 4.4 shows the total emissions generated from both concrete and transportation. Figure 4.2 shows baseline CO_2 emission generated for concrete and cement transportation while figure 4.3 shows graphical representation of baseline CO_2 generated. The material requirements per cubic meter of concrete are as follows:

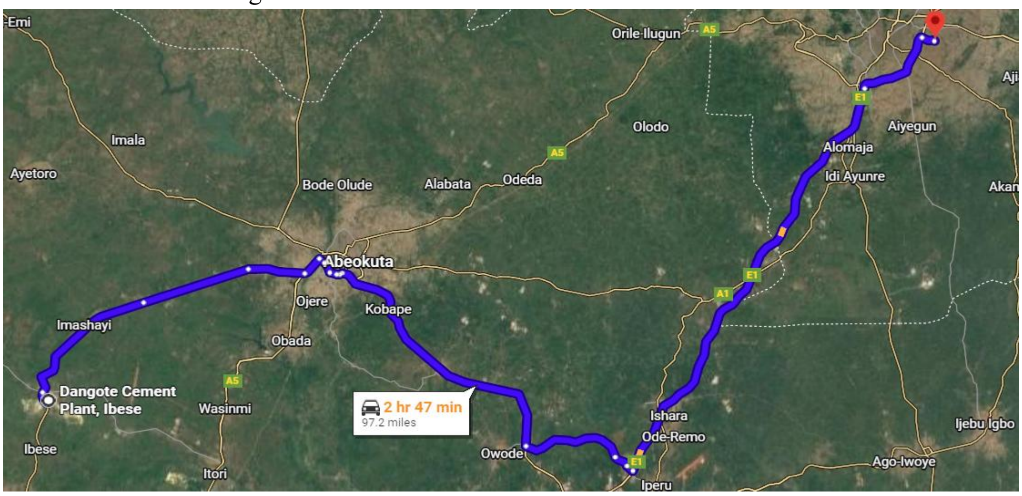

Figure 4.1. Distance Coverage from Cement production factory to site location

Cement:7.92bags. 7.92 × 50 kg/bag = 396 kg, Fine Aggregate: 0.64 tonnes, Coarse Aggregate: 1.12 tonnes

According to Desnz (2024) Emission Factors, the transport emission factor for a 33-ton articulated truck is:0.0912 kg CO_2 per tonne.km
For a 30-mile trip, the emission per kilogram of cement is calculated as:

$$\text{Emission per kg} = \frac{30 \times 1.61 \times 0.0912}{1000} = 0.00440496 \text{ kg } CO_2$$

The route from Ibese to Ibadan covers 97.2 miles. Therefore, the emission per kilogram of cement for this distance is:

$$\text{Emission per kg} = 0.00440496 \times \frac{97.2}{30} = 0.0143 \text{ kg } CO_2$$

Table 3. Baseline CO_2 Emission Generate During Transportation of cement per Story

Storey	Column	Beam	Slab	Foundation	Total	Co_2 Emission
	Kg	Kg	Kg	Kg	Kg	Kg
Footings	934.16	15,496.27	13,764.56	44,617.72	74,812.72	1,069.82
1	6,036.23	8,357.18	13,798.22	0.00	28,191.64	403.14
2	6,036.23	8,357.18	13,798.22	0.00	28,191.64	403.14
3	6,036.23	8,357.18	13,798.22	0.00	28,191.64	403.14
4	6,036.23	8,357.18	13,798.22	0.00	28,191.64	403.14
5	6,036.23	8,357.18	0.00	0.00	14,393.41	205.83
Total	31,115.30	57,282.19	68,957.46	44,617.72	201,972.67	2,888.21

Table 4. Optimized concrete extraction summary by storey and element (m^3)

Storey	Concrete Emission	Transport Emission	Total CO_2 Emission
	Kg	Kg	Kg
Footings	60,455.04	1,069.82	61,524.86
1	22,781.44	403.14	23,184.58
2	22,781.44	403.14	23,184.58
3	22,781.44	403.14	23,184.58
4	22,781.44	403.14	23,184.58
5	11,631.36	205.83	11,837.19
Total	163,212.16	2,888.21	166,100.37

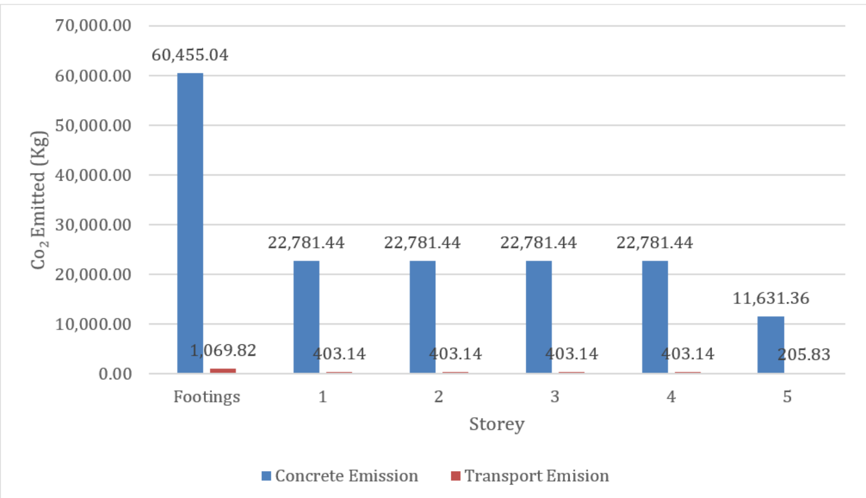

Figure1. Baseline CO_2 Emission Generated for Concrete and Cement transportation

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DOI: https://doi.org/10.64388/IREV9I7-1713754

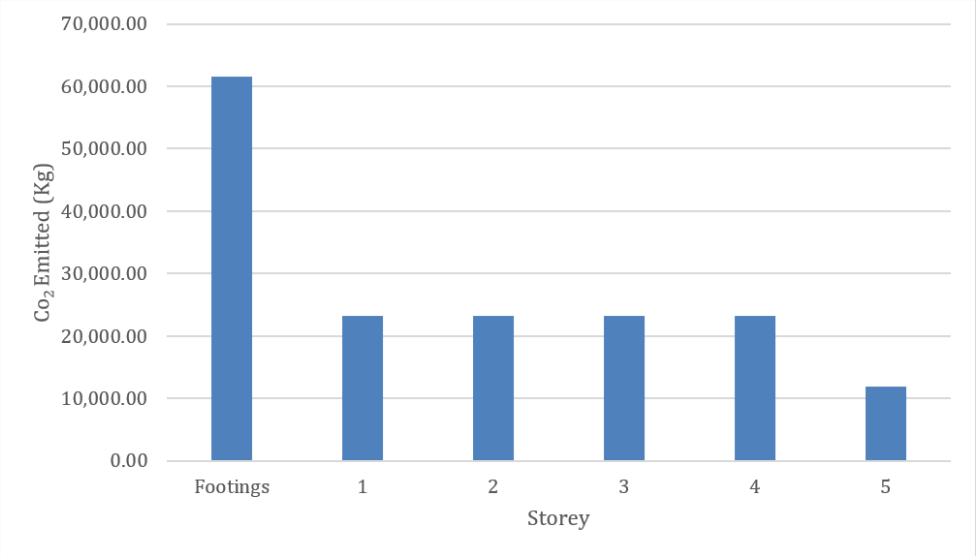

Figure 4.3. Graphical Representation of baseline CO_2 Generated

4.3 Optimized Design Analysis
As shown in table 5, optimized design reduced the total concrete volume to 435.738 m³, corresponding to 139,436.16 kg (139.44 tonnes) in table 4.6 of CO_2 emissions. Table 4.7 shows optimized CO_2 emission generate during transportation of cement per story while table 4.8 shows the total CO_2 emission generate per storey. Figure 4.9 shows optimized CO_2 emission generated for concrete and cement transportation while figure 4.10 shows graphical representation of optimized CO_2 generated. Figure 4.11 and 4.12 show section parameters for the optimized design.

Table 5. Optimized Concrete Extraction Summary

Storey	Column (m^3)	Beam (m^3)	Slab (m^3)	Foundation (m^3)	Total (m^3)
Foundation	2.359	39.132	26.187	112.671	180.35
1	14.636	15.935	29.037	0	59.608
2	14.636	15.935	29.037	0	59.608
3	14.838	15.935	29.037	0	59.81
4	10.383	15.935	29.037	0	55.355
5	10.383	10.623	0	0	21.007
TOTAL	67.236	113.495	142.335	112.671	435.738

Table 6. Optimized CO_2 Emission Per Story

Storey	Column (M^3)	Beam (M^3)	Slab (M^3)	Foundation (M^3)	Total (M^3)	Co_2 Emission 320kg/m^3
Foundation	2.359	39.132	26.187	112.671	180.35	57,712.00
1	14.636	15.935	29.037	0	59.608	19,074.56
2	14.636	15.935	29.037	0	59.608	19,074.56
3	14.838	15.935	29.037	0	59.81	19,139.20
4	10.383	15.935	29.037	0	55.355	17,713.60

5	10.383	10.623	0	0	21.007	6,722.24
TOTAL	67.236	113.495	142.335	112.671	435.738	139,436.16

Table 7. Optimized CO_2 Emission Generate During Transportation of cement per Story

Storey	Column kg	Beam kg	Slab kg	Foundation kg	Total kg	Co_2 Emission kg
Foundation	934.16	15,496.27	10,370.05	44,617.72	71,418.20	1,021.28
1	5,795.86	6,310.26	11,498.65	0.00	23,604.77	337.55
2	5,795.86	6,310.26	11,498.65	0.00	23,604.77	337.55
3	5,875.85	6,310.26	11,498.65	0.00	23,684.76	338.69
4	4,111.67	6,310.26	11,498.65	0.00	21,920.58	313.46
5	4,111.67	4,206.71	0.00	0.00	8,318.38	118.95
TOTAL	26,625.46	44,944.02	56,364.66	44,617.72	172,551.85	2,467.49

Table 8. Optimized CO_2 Emission Generate per Storey

Storey	Concrete Emission Kg	Transport Emision Kg	Total Co_2 Emission Kg
Foundation	57,712.00	1,021.28	58,733.28
1	19,074.56	337.55	19,412.11
2	19,074.56	337.55	19,412.11
3	19,139.20	338.69	19,477.89
4	17,713.60	313.46	18,027.06
5	6,722.24	118.95	6,841.19
TOTAL	139,436.16	2,467.49	141,903.65

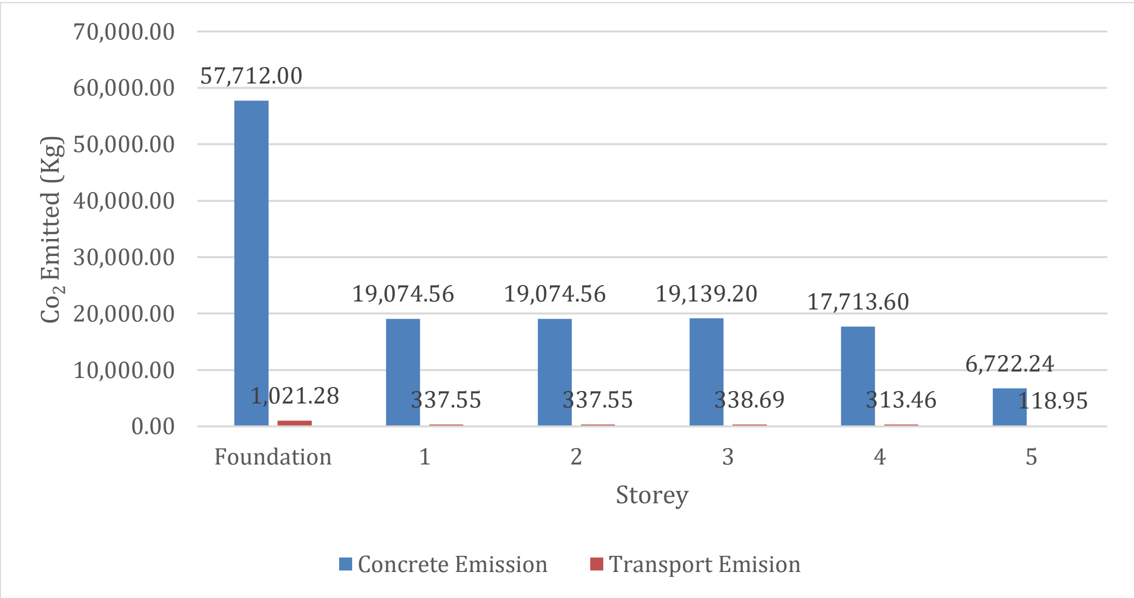

Figure 4.9. Optimized CO_2 Emission Generated for Concrete and Cement Transportation

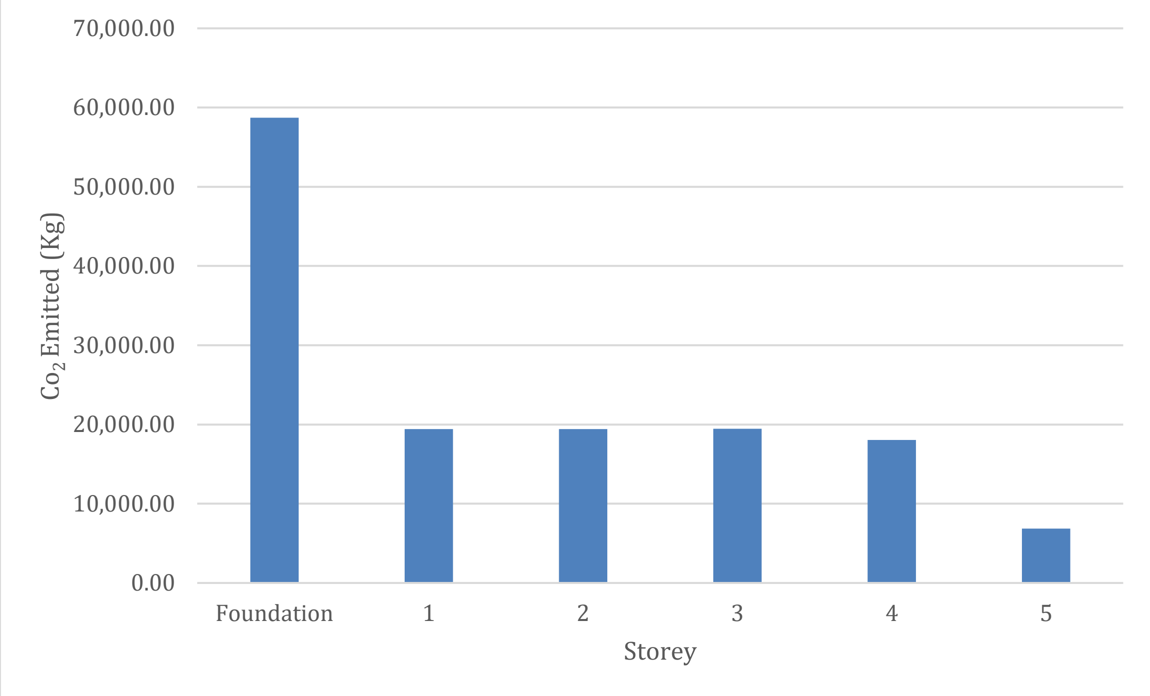

Figure 4.1. Graphical Representation of optimized CO_2 Generated

4.4 Comparative Analysis

Table 4.9 and 4.10 show the comparative analysis between the baseline and optimized designs reveals a clear reduction in both concrete volume and associated CO_2 emissions. The baseline design emitted 163,212.16 kg of CO_2, while the optimized design emitted 139,436.16 kg, representing a 14.57% reduction. The graphical representation is shown in figure 4.13.

Table 9. Bassline and Optimized Emission Comparison

	Baseline Co_2 Emission		Optimized Co_2 Emission	
Storey	Concrete Emission Kg	Transport emission Kg	Concrete Emission Kg	Transport emission Kg
Footings	60,455.04	1,069.82	57,712.00	1,021.28
1	22,781.44	403.14	19,074.56	337.55
2	22,781.44	403.14	19,074.56	337.55
3	22,781.44	403.14	19,139.20	338.69
4	22,781.44	403.14	17,713.60	313.46
5	11,631.36	205.83	6,722.24	118.95
Total	163,212.16	2,888.21	139,436.16	2,467.49

Table 10. CO_2 Emission Comparative Table

Storey	Baseline Co_2 Emission Kg	Optimized Co_2 Emissiom Kg
Footings	61,524.86	58,733.28
1	23,184.58	19,412.11
2	23,184.58	19,412.11
3	23,184.58	19,477.89
4	23,184.58	18,027.06
5	11,837.19	6,841.19
Total	166,100.37	141,903.65

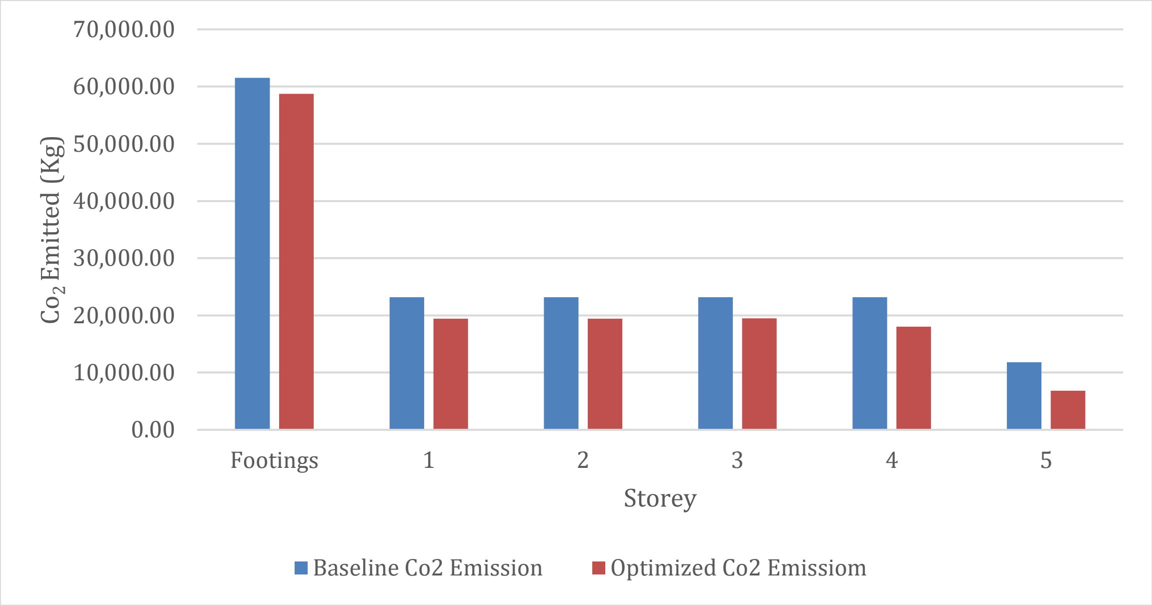

Figure 4.2. CO_2 Emission Comparative Chart

$$\text{Reduction (\%)} = \frac{\text{Baseline Emissions} - \text{Optimized Emissions}}{\text{Baseline Emissions}} \times 100$$

$$\text{Carbon Reduction percentage} = \frac{166{,}100.37 - 141{,}903.65}{166{,}100.37} \times 100 = 14.57\%$$

V. DISCUSSION

The findings corroborate literature that material-efficient structural design can significantly curb embodied emissions in concrete construction. Resizing slabs, beams, and columns reduced total concrete volume by approximately 14.6%, closely tracking the 14.57% reduction in total CO_2. Because foundations remained unchanged and represent a major share of volume, further reductions could be realized through alternative binders (e.g., SCMs), optimized foundation systems, and performance-based specifications that safely lower paste content. Transport contributed a smaller but non-negligible portion of emissions; sourcing cementitious materials closer to site and improving logistics can deliver incremental gains. Integrating BIM and LCA early enabled a transparent comparison of scenarios and helped target the most effective interventions.

VI. CONCLUSIONS AND PRACTICAL IMPLICATIONS

This case demonstrates a practical, replicable pathway for achieving immediate embodied carbon reductions using structural optimization within a BIM–LCA framework. A 14.57% reduction in total CO_2 was achieved without compromising structural performance. The workflow can be generalized to similar commercial projects and adapted to different contexts by updating emission factors and logistics data. Future work should evaluate clinker substitution levels, alternative cements, recycled aggregates, and durability-informed design to guard against rebound effects and ensure life-cycle benefits.

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