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BIM-Based Embodied-Carbon Assessment of Sustainable Concrete Mixtures Incorporating Fly Ash, GGBS, and Silica Fume: A Progressive Element-to-Building Framework for Bahrain

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Abstract

Reducing the carbon emissions associated with reinforced-concrete materials requires effective comparison of material alternatives before project-scale implementation. This study develops and demonstrates a progressive element-to-building environmental assessment framework that combines quantity extraction from Autodesk Revit with global warming potential (GWP) factors obtained from IDEMAT. Following benchmark checks, a standardized reinforced-concrete beam measuring 3.0 m × 0.20 m × 0.40 m was used to screen 25 concrete mixture scenarios comprising ordinary Portland cement (OPC), single supplementary cementitious materials (SCMs), binary SCM blends, and ternary SCM blends. Selected scenarios were subsequently applied to two residential building information modeling (BIM) models in Bahrain. Assuming a common target compressive strength of 35 MPa, the calculated carbon emissions per beam were 119.7 kg CO_2e for OPC concrete, compared with 76.8, 76.5, and 75.7 kg CO_2e for the G60, B6, and T5 mixtures, respectively. Across the two residential buildings, the calculated structural-system GWP decreased from 94.99 t CO_2e for OPC to 60.05 t CO_2e for T5, representing a reduction of approximately 36.8%. These comparisons are conditional on the adopted mixture assumptions and emission factors; equivalent mechanical and durability performance was not experimentally verified. The assessment is limited to the defined system boundary and does not constitute a whole-life carbon assessment. BIM enables project-scale comparisons by linking environmental estimates to material quantities and their distribution across structural elements.

Keywords: building information modeling (BIM); global warming potential (GWP); supplementary cementitious materials (SCMs); reinforced concrete; embodied carbon; carbon emissions assessment

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1. Introduction

The environmental impact of construction materials is increasingly important as the operational energy performance of buildings improves. In this study, the structural embodied carbon refers to the calculated global warming potential (GWP) of the modeled reinforced-concrete materials within the explicitly defined assessment boundary; it does not represent a complete life-cycle assessment of concrete or a whole-building whole-life-carbon assessment. Reinforced concrete warrants particular attention because of its extensive use

in buildings and the carbon intensity of ordinary Portland cement (OPC) production [1–4]. Partial replacement of OPC with supplementary cementitious materials (SCMs), including fly ash (FA), ground granulated blast-furnace slag (GGBS), and silica fume (SF), can reduce the calculated GWP of concrete, depending on the constituent materials, their emission factors, and the mixture proportions [5]. Fly ash use and supplementary cementing materials are discussed in established technical references [6,7], while silica-fume-specific guidance is available from ACI Committee 234 [8]. However, the engineering performance of SCM-modified concrete depends on binder chemistry, constituent properties, replacement levels, curing conditions, and mixture design. Research on slag–fly ash geopolymers and SCM-modified concrete under different moisture and service conditions further demonstrates why environmental screening alone cannot establish equivalent compressive strength or durability [9–12].

Recent research on cement-based materials further demonstrates that environmental assessment should be considered alongside material performance. For example, Zheng et al. investigated the static and cyclic hydro-mechanical behavior of cement stone reinforced using fiber-carrier-encapsulated microbially induced calcium carbonate precipitation (MICP), highlighting the influence of material modification on strength, impermeability, and performance under cyclic loading [13]. Although this study addresses a different cementitious system from the supplementary cementitious material (SCM) mixtures considered here, it reinforces the importance of distinguishing calculated environmental benefits from demonstrated engineering performance. Accordingly, the present study evaluates the global warming potential of alternative binder systems while explicitly recognizing that their mixture-specific mechanical and durability performance requires independent experimental verification.

At building scale, building information modeling (BIM) can connect digital geometry and material quantities with life-cycle inventory or environmental-impact factors. BIM–LCA research has shown that this integration can support sustainability assessment and early design decisions by reducing repetitive quantity take-off and enabling alternatives to be compared systematically [14–17]. Recent building studies have extended these methods to residential whole-life carbon assessment and building-level carbon-reduction strategies [16,17]. Integrated BIM–LCA–decision frameworks have also been used to compare conventional and SCM-based concrete alternatives [18]. Nevertheless, the reliability of any integrated workflow depends on both the quantity model and the environmental dataset, while geography, production technology, allocation, transport, and system boundaries can materially affect absolute GWP values [19–22].

Recent material-level studies confirm that SCM substitution can reduce calculated concrete GWP, but environmental preference must be interpreted alongside engineering requirements. Work on slag/fly-ash-based binders shows that constituent chemistry and mineralogical characteristics can alter reaction mechanisms and mechanical response; studies of SCM-modified concrete also report sensitivity of moisture evolution, shrinkage, hydration, and freeze–thaw behavior to constituent proportions and exposure conditions [9–12,23,24]. These studies concern different material systems and are cited here to establish the general need for performance validation, not as direct evidence that the mixtures examined in this paper achieve a particular strength class. A remaining methodological issue is how to compare a relatively large set of candidate binder systems efficiently before committing to full building-level scenario modeling.

The novelty of this study therefore does not lie in demonstrating that SCM replacement can reduce cement-related GWP, which is well established. Rather, the contribution is a transparent progressive workflow that: (i) independently checks the adopted BIM quantity-extraction and environmental-calculation procedures against published bench-

marks; (ii) screens 25 single-, binary-, and ternary-SCM scenarios under identical reinforced-concrete element conditions; and (iii) transfers only the leading alternatives to two BIM-based residential buildings to quantify absolute savings, floor-area-normalized intensities, and the structural elements in which mitigation opportunities are concentrated. This separation of material ranking from project-scale quantification reduces repeated building-level scenario work while retaining the practical information provided by BIM.

Accordingly, the study aims to quantify the relative GWP performance of the investigated SCM systems, determine their building-scale carbon implications in two Bahrain residential case studies, and critically assess the value and limitations of the element-to-building screening strategy. The work is an environmental decision-support analysis rather than a complete multi-objective concrete optimization or experimental performance-validation study.

2. Materials and Methods

2.1. Research Framework

The research followed a staged workflow: (i) benchmark checks of Revit quantity extraction and IDEMAT-based calculations; (ii) screening of 25 binder scenarios using one standardized beam with fixed geometry and reinforcement; and (iii) application of selected scenarios to two BIM-based residential buildings. Figure 1 summarizes the workflow. The life-cycle terminology follows EN 15804 [25]: A1 denotes raw-material supply, A2 transport to manufacturing, A3 manufacturing, A4 transport to the construction site, B1 use-stage carbonation in the adopted inventory, and C1–C4 end-of-life processes. In the comparative beam calculation, only A1 material supply was recalculated for each mixture; A2, A3, A4, B1, and C1–C4 were held fixed. Consequently, the assessment is a common-inventory screening exercise rather than a supply-chain-specific cradle-to-grave LCA. A2 and A4 are not SCM-specific, and their fixed values do not capture differing origin, transport distance, processing, or allocation for FA, GGBS, and SF. These limitations are addressed in the Discussion Section.

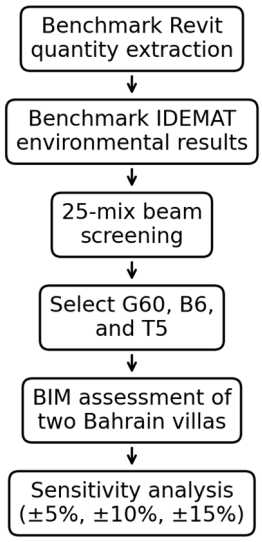


Figure 1. Progressive environmental assessment framework used in the study.

2.2. Benchmark Assessment of Revit Quantity Extraction

A published reinforced-concrete residential building was reconstructed in Autodesk Revit 2025 using the available geometric, structural, and material information [16]. Revit schedules were generated for concrete volume and reinforcement mass and compared with the published quantities. The percentage difference was calculated as

|QRevit − Qref|/Qref × 100. This benchmark assesses the specific modeling and scheduling procedure adopted in the present study; it does not constitute universal validation of Autodesk Revit.The comparison between published reference quantities and quantities extracted using Autodesk Revit 2025 is presented in Table 1.

Table 1. Comparison of published and Revit-extracted quantities.

Difference	Revit Quantity	Published Quantity	Material	Structural Element
0.81%	9.76 m^3	9.84 m^3	Concrete	Foundation
0.79%	897 kg	890 kg	Reinforcement	Foundation
0.40%	14.87 m^3	14.93 m^3	Concrete	Slab
0.93%	1.09 m^3	1.08 m^3	Concrete	Column
1.29%	153 kg	155 kg	Reinforcement	Column
0.95%	1.06 m^3	1.05 m^3	Concrete	Beam
1.11%	178 kg	180 kg	Reinforcement	Beam

2.3. Benchmark Assessment of the Environmental Calculation

The IDEMAT-based calculation was checked against published reinforced-concrete GWP data [19]. The OPC beam result is 119.7 kg CO_2e, including 38.300 kg CO_2e from 24 kg of reinforcement. The A1 subtotal is 119.161 kg CO_2e; subtracting reinforcement gives 80.861 kg CO_2e for the concrete at A1, equivalent to 336.9 kg CO_2e/m^3 for the 0.24 m^3 beam. Adding the fixed A2 transport (2.683 kg/beam) and A3 manufacturing (0.434 kg/beam) contributions gives 83.978 kg CO_2e/beam, or 349.9 kg CO_2e/m^3 for the concrete A1–A3 contribution. The latter is approximately 4.8% above the 334 kg CO_2e/m^3 benchmark [19]. The comparison is a consistency check, not independent validation, because the studies differ in database, geography, mixture assumptions, and system boundary.

2.4. Beam-Based Parametric Screening

A standardized reinforced-concrete beam was adopted as the common environmental-screening unit. Its dimensions were 3.0 m × 0.20 m × 0.40 m (0.24 m^3), with 24 kg of reinforcement. The stated 35 MPa concrete strength is a commonly assumed design class used to define the comparison, not a measured or literature-verified property for each of the 25 mixtures. No experimental program was conducted, and no mixture-specific 28-day strength, specimen type, workability, shrinkage, or durability result is claimed. Thus, the high-replacement mixtures are environmental scenarios requiring subsequent mix design and performance validation before structural use. The geometry and reinforcement details adopted for the standardized beam are summarized in Table 2.

Table 2. Beam specification used for environmental screening.

Value	Parameter
3.0 m	Length
0.20 m	Width
0.40 m	Overall depth
35 MPa	Assumed target compressive strength
460 MPa	Reinforcement yield strength
2T16	Top reinforcement
2T16	Bottom reinforcement
T6 at 200 mm c/c	Stirrups

For each material i, its calculated contribution was obtained from $EC_i = Q_i \times EF_i$, where Q_i is the material quantity and EF_i is the adopted GWP factor. The total beam

result was EC_total = $\Sigma(Q_i \times EF_i)$ + fixed A2–C4 contributions, and the reduction relative to OPC was R = [(EC_OPC − EC_SCM)/EC_OPC] × 100%. The assessment comprised 25 scenarios: one OPC control, 13 single-SCM mixtures, six binary mixtures, and five ternary mixtures. "Binary" means that two SCM types are used alongside OPC; "ternary" means that three SCM types are used alongside OPC. The terms refer to the number of SCM types, not the total number of binder constituents. Appendix A reports the screening results, and Appendix A reports the assumed constituent quantities per cubic metre. The global warming potential factors assigned to the constituent materials in the beam calculations are listed in Table 3.

$$EC_i = Q_i \times EF_i$$

$$EC_total = \Sigma_i (Q_i \times EF_i) + EC_fixed$$

$$R\ (\%) = [(EC_OPC - EC_SCM)/EC_OPC] \times 100$$

Table 3. Environmental factors used in the beam calculations.

Inventory Entry/Role	GWP Factor (kg CO_2e/kg)	Material
Primary binder	0.903	Portland cement (CEM I)
Fine aggregate	0.0044	Sand
Coarse aggregate	0.0084	Crushed gravel
Admixture	1.880	Polycarboxylate ether
Mixing water	0.0006	Tap water
Hot-rolled reinforcing bar	1.596	Reinforcing steel
SCM	0.0040	Fly ash
SCM	0.0520	GGBS
SCM	0.0140	Silica fume

The factors in Table 3 are the values recorded in the study's IDEMAT calculation inventory, not verified Bahrain-specific environmental product declarations (EPDs). The particularly low factors assigned to FA and SF and the low factor assigned to GGBS strongly influence the calculated results. SCM burdens can vary with allocation rules, processing, product specification, geography, and transport. Therefore, the reported reductions should be read as "lowest calculated GWP under the adopted inventory," not as a universal environmental ranking. Regional EPDs and supplier-specific distances are required for project decisions. To make factor dependence explicit, an additional factor stress test is reported in Section 3.4; the multipliers used there are analytical stress tests, not claims about market-average factors.

The inventory uses selected life-cycle modules described using EN 15804 terminology [25]. A1 covers raw-material supply and is the only module recalculated across binder scenarios. A2 transport, A3 manufacturing, A4 distribution to site, B1 carbonation, and C1–C4 end-of-life contributions were held constant at 2.683, 0.434, 0.991, −3.600, and 0.000 kg CO_2e per beam, respectively; their net contribution is +0.508 kg CO_2e/beam. The fixed transport assumptions use 8.4 tkm for cement/SCM and 22.8 tkm for aggregates for the beam, without distinguishing supplier-specific SCM routes. This simplification enables controlled comparison but does not represent the different transport and processing burdens that may apply to imported silica fume, GGBS, or locally/regionally sourced FA. The results therefore represent a comparative inventory, not a regionally complete A1–C4 footprint for each supply chain. Module definitions are introduced here before their use in the calculations.

2.5. BIM-Based Building Assessment

The selected single-SCM, binary-SCM, and ternary-SCM scenarios were transferred to Autodesk Revit 2025 models of two reinforced-concrete residential villas in Bahrain. Structural concrete volumes were 57.081 m^3 for Villa A and 133.433 m^3 for Villa B; gross floor areas were 181.2 m^2 and 390.84 m^2, respectively. Four cases were evaluated for each building: OPC, G60, B6, and T5. The same geometry and structural quantities were maintained across scenarios. Revit schedules provide consistent, traceable quantity take-off by structural element and building, enabling calculation of absolute project-scale differences, floor-area-normalized intensity, and the elements contributing most to the total. Because the material factors are applied to unchanged quantities, BIM does not independently validate the material ranking; it adds project-specific quantity and distribution information beyond a beam-level result. No structural redesign, change in reinforcement, or mixture-specific performance optimization is modeled.

2.6. Deterministic Quantity Sensitivity Analysis

A deterministic quantity sensitivity analysis varied structural quantities by −15%, −10%, −5%, +5%, +10%, and +15%, while material factors and mixture compositions were held constant. This tests the scaling of absolute GWP values but does not test uncertainty in the factors driving the close G60–B6–T5 differences. A further EPD-informed cross-dataset scenario used 0.0654 kg CO_2e/kg for FA (the A1–A3 GWP-total result in the JSW Energy dry-fly-ash EPD [26]) and 0.155 kg CO_2e/kg for GGBS (the A1–A3 factor reported by MPA Cement [27]), while retaining the study's SF factor and all the other assumptions. Because these values originate from different product declarations and allocation/system-boundary conventions, this is a stress test rather than a like-for-like regional inventory. Common 2× and 5× multipliers for all three SCM factors were also tested as transparent stress scenarios. These tests do not replace regional EPD data or a probabilistic uncertainty analysis.

3. Results

3.1. Benchmark Results

All the Revit quantity differences in the benchmark comparison were below 1.5%. The IDEMAT calculation gave 336.9 kg CO_2e/m^3 for the concrete A1 contribution and 349.9 kg CO_2e/m^3 for the concrete A1–A3 contribution. The latter is approximately 4.8% higher than the 334 kg CO_2e/m^3 benchmark [19]. The distinction is important: 119.669 kg CO_2e is the full reinforced-concrete beam result, 336.9 kg CO_2e/m^3 is the concrete-only A1 result, and 349.9 kg CO_2e/m^3 includes the fixed A2 and A3 contributions. The comparison supports consistency of scale, but does not establish a universally valid Bahrain factor.

3.2. Screening of 25 Concrete Mixtures

The OPC control beam produced 119.7 kg CO_2e under the adopted inventory, of which reinforcement contributed 38.300 kg CO_2e (approximately 32.0%). Among the single-SCM cases, FA30 reduced calculated beam GWP by 18.9%, G60 by 35.8%, and SF15 by 9.4%. B6 (50% GGBS + 10% SF) reduced the calculated value by 36.1%, while T5 (20% FA + 30% GGBS + 10% SF) gave the lowest calculated GWP under the adopted inventory: 75.7 kg CO_2e, a 36.8% reduction. These figures describe inventory-based environmental screening only and do not establish equivalent 35 MPa performance. The selected control, single-SCM, binary-SCM, and ternary-SCM mixtures are compared in Table 4. Figure 2 presents the calculated GWP for all 25 mixtures; the dashed horizontal line at 120 kg CO_2e marks the approximate GWP of the OPC control mixture and provides a reference for comparing the alternatives.

Table 4. Mixtures with the lowest calculated GWP in each SCM category under the adopted inventory.

Reduction vs. OPC	Beam GWP (kg CO_2e)	Composition	Mix	Category
—	119.7	100% OPC	OPC	Control
35.8%	76.8	40% OPC + 60% GGBS	G60	Best single
36.1%	76.5	40% OPC + 50% GGBS + 10% SF	B6	Best binary
36.8%	75.7	40% OPC + 20% FA + 30% GGBS + 10% SF	T5	Best ternary

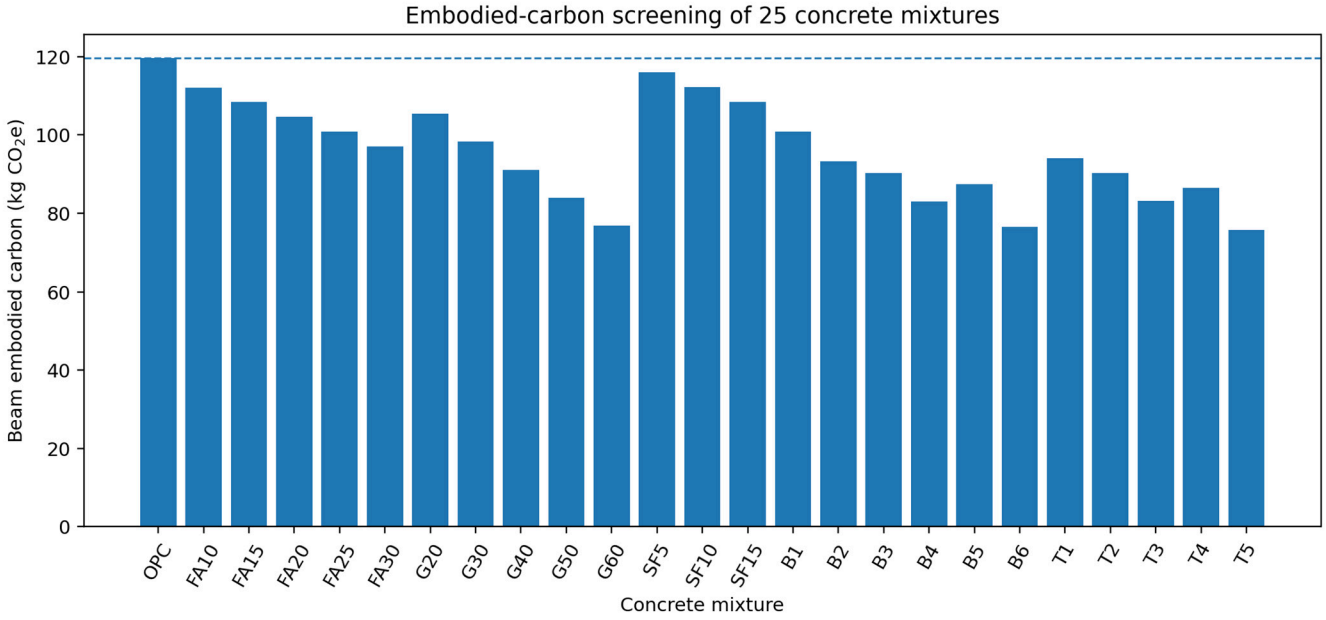


Figure 2. Calculated beam GWP for the 25 investigated concrete mixtures under the adopted inventory.

The three selected alternatives are closely ranked under the base inventory: B6 improves the calculated reduction relative to G60 by only 0.3 percentage points, and T5 improves it by 1.0 percentage point. Because emission-factor uncertainty may be comparable to or larger than these differences, the values should not be interpreted as a definitive universal ranking. Section 3.4 presents an illustrative SCM-factor stress test, while performance feasibility remains outside the evidence generated by this study.

Main-text beam GWP values are rounded to one decimal place because the environmental factors do not justify milligram-level or three-decimal interpretive precision; Appendix A retains the underlying calculation values for traceability. Interpretation should focus on the relative scale and inventory limitations.

3.3. Building-Level Results

The building-level values followed the same ordering because the same structural quantities were multiplied by the selected material factors. For Villa A, the calculated structural-system GWP decreased from 28.462 t CO_2e for OPC to 17.993 t CO_2e for T5; for Villa B, it decreased from 66.532 to 42.061 t CO_2e. These are calculated impacts for the modeled reinforced-concrete structural system within the stated inventory, not whole-building or complete life-cycle results. The calculated building-level GWP values for the OPC, G60, B6, and T5 scenarios are reported in Table 5. Figure 3 illustrates these calculated structural-system GWP values for Villa A, Villa B, and the combined total across the four scenarios.

Table 5. Building-level calculated GWP for the modeled structural systems.

Reduction vs. OPC	Combined (t CO_2e)	Villa B (t CO_2e)	Villa A (t CO_2e)	System
—	94.994	66.532	28.462	OPC
35.8%	60.947	42.687	18.261	G60
36.1%	60.694	42.509	18.185	B6
36.8%	60.054	42.061	17.993	T5

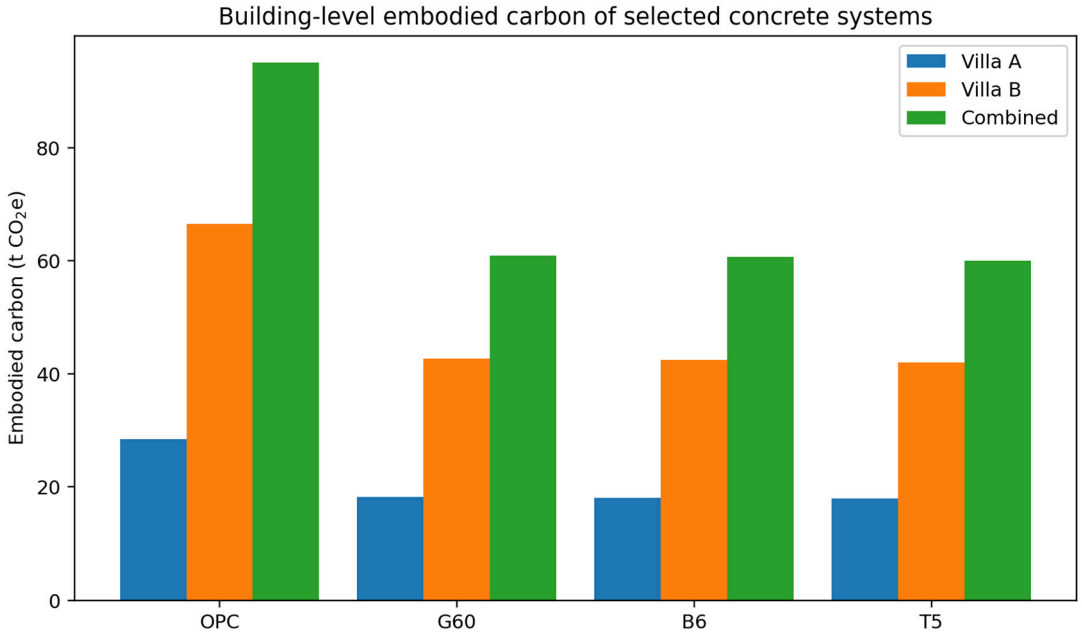


Figure 3. Calculated structural-system GWP of the selected concrete scenarios for the two villas.

For both villas combined, T5 reduced the calculated structural-system GWP from 94.994 to 60.054 t CO_2e, a difference of 34.940 t CO_2e (36.8%) under the adopted inventory. Slabs and substructure elements together accounted for a substantial share of the total because of their quantities. Since the scenario ranking is inherited from the material factors applied to fixed quantities, the building analysis should be understood as project-scale quantification and spatial allocation of potential savings, not independent confirmation that T5 is technically or environmentally superior under all local supply conditions. The corresponding structural embodied-carbon intensities normalized by gross floor area are presented in Table 6.

Table 6. Structural embodied-carbon intensity normalized by gross floor area.

Villa B (kg CO_2e/m^2 GFA)	Villa A (kg CO_2e/m^2 GFA)	System
170.23	157.07	OPC
109.22	100.78	G60
108.76	100.36	B6
107.62	99.30	T5

Normalization by gross floor area shows that Villa B has a higher structural embodied-carbon intensity than Villa A for every material scenario. This demonstrates an additional value of the BIM stage: although the percentage reduction caused by a given binder is controlled by the material factors, BIM-derived project geometry and structural quantities determine the absolute and area-normalized carbon intensity of each building.

3.4. Sensitivity Results

Proportional changes in structural material quantities changed the absolute GWP values in the same direction and approximately the same proportion. At −15%, the combined values were 80.745 t CO_2e for OPC and 51.046 t CO_2e for T5; at +15%, the corresponding values were 109.243 and 69.062 t CO_2e. The ordering T5 < B6 < G60 < OPC did not change because quantities were varied while environmental factors and mixture compositions were fixed. Figure 4 shows this proportional response in the combined building-level GWP as structural material quantities vary from −15% to +15%.

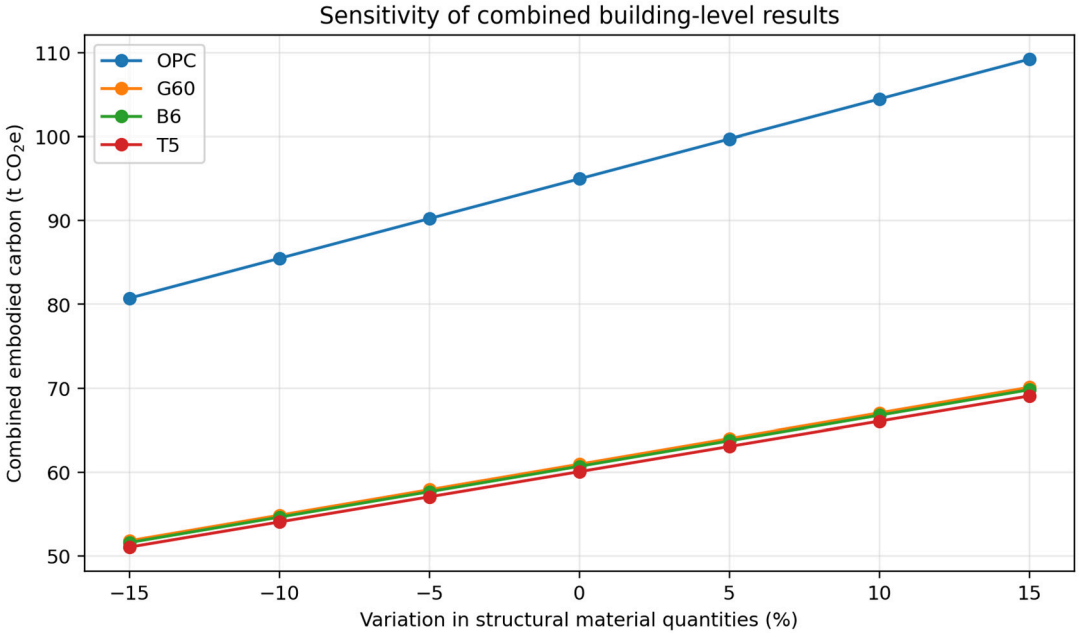


Figure 4. Sensitivity of combined building-level calculated GWP to material-quantity variation.

The linear response confirms that the quantity analysis is a scaling check, not evidence that the close G60–B6–T5 ranking is robust to environmental-factor uncertainty. To address this distinction, the additional factor stress test in Section 3.4 varies the three SCM factors simultaneously. Even this deterministic test does not cover all the possible allocation methods, production routes, transport distances, or local EPD values; it is used only to show how the chosen ranking responds to transparent alternative factor assumptions.

Illustrative SCM Emission-Factor Stress Test

To test dependence on the adopted SCM factors, FA, GGBS, and SF factors were multiplied together by 2 and by 5, while all the other factors, quantities, and fixed modules were held constant. These multipliers are deliberately transparent stress-test scenarios and are not claimed to represent measured regional ranges. For the 0.24 m^3 beam, the relevant SCM quantities are G60: 50.4 kg GGBS; B6: 42.0 kg GGBS and 8.4 kg SF; and T5: 16.8 kg FA, 25.2 kg GGBS, and 8.4 kg SF. The calculated totals for the base, common-multiplier, and EPD-informed scenarios are presented in Table 7. The ordering remains T5, B6, G60 in these particular common-multiplier tests; however, this does not establish robust ranking under independent factor changes, alternative allocation, or region-specific transport and processing. Because the base differences are small, the exact ranking should be reported as inventory-dependent.

Table 7. Illustrative sensitivity of selected beam GWP results to common multipliers applied to SCM emission factors.

SCM-Factor Scenario	G60 (kg CO_2e/Beam)	B6 (kg CO_2e/Beam)	T5 (kg CO_2e/Beam)	Ordering
Base factors	76.8	76.5	75.7	T5 < B6 < G60
FA, GGBS and SF factors × 2	79.4	78.8	77.1	T5 < B6 < G60
FA, GGBS and SF factors × 5	87.3	85.7	81.6	T5 < B6 < G60
EPD-informed FA/GGBS factors *	82.0	80.8	79.3	T5 < B6 < G60

* The EPD-informed scenario applies FA = 0.0654 and GGBS = 0.155 kg CO_2e/kg, with SF retained at 0.014 kg CO_2e/kg. The FA value is from the JSW Energy Dry Fly Ash EPD (registration EPD-IES-0022639:002; GWP-total A1–A3 = 65.4 kg CO_2e/t) [26]; the GGBS value is from MPA Cement Fact Sheet 18 (155 kg CO_2e/t) [27]. Differences in datasets, allocation, and product context mean these are illustrative alternatives, not Bahrain-specific or strictly harmonized factors.

4. Discussion

The principal methodological contribution is the separation of material-scenario screening from project-scale quantification. Twenty-five concrete scenarios were first compared under a common beam geometry and reinforcement arrangement, allowing candidate mixtures to be screened without repeatedly rebuilding the two building models. The subsequent BIM stage provides more than a single multiplication of beam results: it quantifies each selected scenario against the actual modeled concrete volumes, reports building-specific and floor-area-normalized totals, and identifies which structural elements dominate the calculated opportunity. Nevertheless, because quantities are fixed and material factors are applied consistently, the ordering of alternatives at building level is mathematically inherited from the beam-level material calculation. BIM therefore supports traceable project-scale application, not independent validation of the material ranking.

This distinction is important when positioning the work relative to previous BIM–LCA research. Recent studies have demonstrated whole-building carbon calculation and BIM-supported reduction strategies [16,17], while integrated BIM–LCA decision frameworks have compared conventional and green concrete alternatives [18]. The present study adds a pre-building screening stage in which a broader set of single, binary, and ternary SCM systems is compared under identical reinforced-concrete conditions before selected systems are transferred to complete BIMs. The workflow is most useful when many material alternatives must be shortlisted but only a smaller number warrant project-level modeling and reporting.

The benchmark stage addresses a second practical issue: numerical precision in a BIM-enabled environmental workflow can obscure uncertainty in both quantity extraction and environmental factors. Revit differences below 1.5% support the adopted quantity procedure for the selected benchmark, while the approximately 4.8% difference in concrete GWP relative to the published 35 MPa reference [19] is reasonable for a comparative consistency check. It does not establish a Bahrain-specific factor. Environmental datasets can vary because of production technology, electricity mix, geographic representativeness, transport, allocation of industrial by-products, and life-cycle boundary assumptions [19–22].

The SCM comparison confirms the dominant influence of the adopted binder emission factors on calculated GWP. G60, B6, and T5 all contain 40% OPC, and their small differences arise from the factors assigned to the remaining SCM constituents. This is precisely why the result should be reported as the lowest calculated GWP under the adopted inventory rather than as a best-performing concrete in a broader engineering sense. Binder chemistry, fineness, reactivity, curing, water-to-binder ratio, and constituent quality can affect strength development and durability; no such performance outcomes were measured here.

Reinforcement is also significant: steel represented approximately 32.0% of the OPC beam GWP. As binder-related emissions decline, reinforcement can constitute a larger

relative share of structural embodied carbon. Material decarbonization should therefore be combined with structurally efficient design, rational member sizing, reinforcement optimization, and avoidance of unnecessary material. Reinforcement strategy also affects structural performance and durability; Meshaly et al. [28], for example, investigated corrosion-resistant reinforcement systems in reinforced-concrete frames, illustrating the broader need to consider reinforcement choice alongside concrete decarbonization.

The floor-area-normalized results further show why project-scale BIM quantification remains useful even when material rankings are predetermined. Villa A and Villa B produced different structural carbon intensities because their structural quantities and configurations differ. Similarly, the concentration of more than 70% of structural concrete in slabs and substructure elements directs attention to components where design optimization or lower-GWP specifications can deliver the largest absolute reductions. Thus, the building stage provides decision information that cannot be obtained from the material ranking alone.

SCM-modified concrete can also respond differently to moisture and exposure conditions. Recent studies on metakaolin-modified UHPC and FA/GGBS concrete under low humidity report changes in internal moisture, shrinkage, hydration, and freeze–thaw response [11,12]. These findings are not direct validation of the mixtures in this study or of Bahrain exposure conditions; they support the need to evaluate durability and service conditions separately from inventory-based GWP.

Limitations and Implications for Future Work

Several limitations define the scope of the conclusions. First, 35 MPa is an assumed common design class, not a verified strength achieved by every mixture; no mixture-specific specimen type, reference age, compressive strength result, workability, shrinkage, or durability test was available. High-replacement scenarios, particularly 60% GGBS, must therefore be treated as environmental screening candidates requiring mix design and experimental validation before structural adoption. Second, the quantities assume a total binder content of 350 kg/m^3, water content of 180 kg/m^3 (water-to-binder ratio 0.514), sand of 700 kg/m^3, crushed gravel of 1200 kg/m^3, and PCE admixture of 4 kg/m^3. Replacement was implemented by mass while keeping total binder mass constant; no density-based absolute-volume correction was applied. Third, the adopted IDEMAT factors are not Bahrain-specific EPDs. Fourth, SCM-specific transport and processing were not modeled; fixed A2–C4 values can obscure regional supply-chain differences, particularly for SF and GGBS. Fifth, the sensitivity analysis is deterministic and does not constitute probabilistic uncertainty analysis. Finally, the two villas represent a limited typology, and the BIM stage does not independently validate material ranking because structural quantities are held constant. Future work should incorporate regional EPDs and supplier distances, mixture-specific experimental testing, durability and service-life assessment, and a broader uncertainty analysis.

5. Conclusions

1. The Revit quantity-extraction procedure reproduced the selected benchmark quantities with differences below 1.5%. The environmental benchmark comparison gave 336.9 kg CO_2e/m^3 for the concrete A1 contribution and 349.9 kg CO_2e/m^3 for the concrete A1–A3 contribution, compared with 334 kg CO_2e/m^3 in the published benchmark. This is a consistency check under different inventories, not universal validation.
2. Under the adopted inventory and assumed mixture quantities, the OPC beam yielded 119.7 kg CO_2e. G60, B6, and T5 yielded 76.8, 76.5, and 75.7 kg CO_2e, respectively. These correspond to calculated reductions of 35.8%, 36.1%, and 36.8%. They are

environmental-screening results; equivalent strength, durability, and workability were not verified.

3. Applying the selected mixtures to the two BIM-based villas quantified project-scale implications for the modeled structural system. T5 reduced the combined calculated GWP from 94.994 to 60.054 t CO_2e under the adopted inventory. The ranking is inherited from material factors applied to fixed quantities, while BIM contributes building-specific quantities, intensity values, and element-level distribution.
4. The deterministic quantity analysis changed absolute GWP values but not scenario ordering because material factors and mixture compositions were fixed. An additional 2× and 5× SCM-factor stress test is reported as an illustrative sensitivity check; it does not replace regional EPD data or probabilistic uncertainty analysis.
5. The main contribution is a transparent progressive workflow for environmental screening and project-scale quantification. The results identify alternatives with lower calculated GWP under the adopted inventory, but technical feasibility, local supply-chain impacts, and service-life performance must be established before these alternatives can be recommended for structural use.

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Appendix A

Table A1 reports the complete beam-level mixture matrix and calculated GWP results; reduction percentages are relative to the OPC reference. The quantities underlying these calculations are summarized in Table A2.

Table A1. Complete beam-level environmental screening matrix.

Reduction vs. OPC	Beam GWP (kg CO_2e)	Binder Composition	Mix
—	119.669	100% OPC	OPC
6.3%	112.118	90% OPC + 10% FA	FA10

Table A1. *Cont.*

Reduction vs. OPC	Beam GWP (kg CO_2e)	Binder Composition	Mix
9.5%	108.341	85% OPC + 15% FA	FA15
12.6%	104.566	80% OPC + 20% FA	FA20
15.8%	100.790	75% OPC + 25% FA	FA25
18.9%	97.014	70% OPC + 30% FA	FA30
11.9%	105.372	80% OPC + 20% GGBS	G20
17.9%	98.224	70% OPC + 30% GGBS	G30
23.9%	91.075	60% OPC + 40% GGBS	G40
29.9%	83.927	50% OPC + 50% GGBS	G50
35.8%	76.779	40% OPC + 60% GGBS	G60
3.1%	115.935	95% OPC + 5% SF	SF5
6.2%	112.201	90% OPC + 10% SF	SF10
9.4%	108.468	85% OPC + 15% SF	SF15
15.7%	100.832	75% OPC + 20% FA + 5% SF	B1
22.0%	93.322	65% OPC + 25% FA + 10% SF	B2
24.6%	90.269	60% OPC + 20% FA + 20% GGBS	B3
30.7%	82.919	50% OPC + 25% FA + 25% GGBS	B4
27.0%	87.342	55% OPC + 40% GGBS + 5% SF	B5
36.1%	76.459	40% OPC + 50% GGBS + 10% SF	B6
21.4%	94.087	65% OPC + 10% FA + 20% GGBS + 5% SF	T1
24.5%	90.311	60% OPC + 15% FA + 20% GGBS + 5% SF	T2
30.5%	83.163	50% OPC + 15% FA + 30% GGBS + 5% SF	T3
27.7%	86.535	55% OPC + 20% FA + 20% GGBS + 5% SF	T4
36.8%	75.653	40% OPC + 20% FA + 30% GGBS + 10% SF	T5

Table A2 reports the assumed mixture quantities used in the beam calculation. A constant total binder content of 350 kg/m^3 was assumed. Cement was replaced by SCMs by mass; constituent densities were not used to correct absolute volume. Sand, gravel, water, and admixture were held constant across scenarios.

Table A2. Assumed concrete mixture quantities per cubic metre used in the beam-level calculations.

Mix	OPC (kg/m^3)	FA (kg/m^3)	GGBS (kg/m^3)	SF (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	PCE (kg/m^3)
OPC	350.0	0.0	0.0	0.0	180.0	700.0	1200.0	4.0
FA10	315.0	35.0	0.0	0.0	180.0	700.0	1200.0	4.0
FA15	297.5	52.5	0.0	0.0	180.0	700.0	1200.0	4.0
FA20	280.0	70.0	0.0	0.0	180.0	700.0	1200.0	4.0
FA25	262.5	87.5	0.0	0.0	180.0	700.0	1200.0	4.0
FA30	245.0	105.0	0.0	0.0	180.0	700.0	1200.0	4.0
G20	280.0	0.0	70.0	0.0	180.0	700.0	1200.0	4.0
G30	245.0	0.0	105.0	0.0	180.0	700.0	1200.0	4.0
G40	210.0	0.0	140.0	0.0	180.0	700.0	1200.0	4.0
G50	175.0	0.0	175.0	0.0	180.0	700.0	1200.0	4.0
G60	140.0	0.0	210.0	0.0	180.0	700.0	1200.0	4.0
SF5	332.5	0.0	0.0	17.5	180.0	700.0	1200.0	4.0
SF10	315.0	0.0	0.0	35.0	180.0	700.0	1200.0	4.0
SF15	297.5	0.0	0.0	52.5	180.0	700.0	1200.0	4.0
B1	262.5	70.0	0.0	17.5	180.0	700.0	1200.0	4.0
B2	227.5	87.5	0.0	35.0	180.0	700.0	1200.0	4.0
B3	210.0	70.0	70.0	0.0	180.0	700.0	1200.0	4.0
B4	175.0	87.5	87.5	0.0	180.0	700.0	1200.0	4.0
B5	192.5	0.0	140.0	17.5	180.0	700.0	1200.0	4.0
B6	140.0	0.0	175.0	35.0	180.0	700.0	1200.0	4.0

Table A2. *Cont.*

Mix	OPC (kg/m^3)	FA (kg/m^3)	GGBS (kg/m^3)	SF (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	PCE (kg/m^3)
T1	227.5	35.0	70.0	17.5	180.0	700.0	1200.0	4.0
T2	210.0	52.5	70.0	17.5	180.0	700.0	1200.0	4.0
T3	175.0	52.5	105.0	17.5	180.0	700.0	1200.0	4.0
T4	192.5	70.0	70.0	17.5	180.0	700.0	1200.0	4.0
T5	140.0	70.0	105.0	35.0	180.0	700.0	1200.0	4.0

Note: Total binder = 350 kg/m^3; water/binder = 180/350 = 0.514. The values are calculation assumptions reconstructed from the thesis appendix, not experimentally optimized mix designs. SCM and cement quantities sum to 350 kg/m^3 in each scenario. Aggregate and admixture quantities are fixed. Density-based absolute-volume correction was not applied.

Worked calculation (beam level). For OPC, the binder contribution is 84.0 kg cement/beam × 0.903 kg CO_2e/kg = 75.852 kg CO_2e. Adding the recorded unchanged contributions for sand (0.743), crushed gravel (2.434), PCE admixture (1.805), water (0.027), and reinforcement (38.300 kg CO_2e/beam) gives an A1 subtotal of 119.161 kg CO_2e; adding the fixed A2–C4 net contribution of 0.508 gives 119.669 kg CO_2e/beam. For T5, the binder contribution is (33.6 × 0.903) + (16.8 × 0.004) + (25.2 × 0.052) + (8.4 × 0.014) = 31.836 kg CO_2e/beam. Adding the same recorded non-binder contributions (0.743 + 2.434 + 1.805 + 0.027 + 38.300 = 43.309 kg CO_2e) gives an A1 subtotal of 75.145 kg CO_2e; adding the fixed 0.508 kg CO_2e yields 75.653 kg CO_2e/beam. Component values are reproduced from the thesis calculation appendix and may reflect rounding and database-entry precision.

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