Pre-Selection Charts for Sustainable Reinforced Concrete Structures

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Abstract

This paper addresses the integration of sustainability considerations into the conceptual design phase of reinforced concrete beam elements, where early design decisions have a decisive influence on material use and environmental impact. A general methodology is proposed for generating sustainability-oriented pre-design charts that support the preliminary selection of beam geometry and concrete strength class. The methodology is based on a repeated Eurocode-constrained optimization procedure. For each combination of design bending moment and concrete strength class, the beam depth and required longitudinal reinforcement are determined in accordance with the flexural design provisions of the Eurocode 2, such that the embodied CO_2 emissions associated with concrete and reinforcing steel (life-cycle stages A1-A3) are minimized. By repeating this procedure over a continuous range of bending moments and multiple concrete strength classes, a consistent set of optimal beam configurations is obtained. These solutions are systematic synthesized into simplified pre-design charts that relate bending moment to optimal beam depth and corresponding embodied CO_2 intensity per meter of beam. The charts provide a compact representation of the trade-offs between concrete strength, member depth, reinforcement demand, and associated environmental impact at the conceptual design stage. In practical terms, they enable engineers to estimate potential reductions in embodied CO_2 by adjusting key design parameters such as concrete class, beam width and effective depth. The proposed methodology is adaptable to regional contexts through the use of location-specific material emission factors and provides a transparent, reproducible, and transferable framework for the development of sustainability-informed pre-design tools for reinforced concrete structures.

Keywords: *Reinforced concrete beams, Ex-ante sustainability design, Low carbon emissions design.*

1. Background, gaps in current practice and contribution

1.1. Introduction

Over recent decades, numerous methodologies have been developed to assess the environmental performance of buildings and construction processes (Lützkendorf 2018). Most rely on Life Cycle Assessment (LCA), which provides comprehensive evaluations of environmental impacts across materials, energy use, and end-of-life stages. In structural design, LCA is commonly applied to compare alternative systems, member geometries, and material options, thereby supporting environmentally informed decision-making. A substantial body of research has examined how material and structural choices affect LCA outcomes. De Paula Filho et al. (2024), for example, compared an office building designed to Eurocode standards using steel–concrete composite, prefabricated reinforced concrete, and timber. Their results identified the steel–concrete composite solution as the most favourable for the investigated case. However, the study did not explore variations within reinforced concrete itself—specifically the influence of different concrete strength classes—leaving an important design parameter unaddressed.

Barbhuiya and Das (2023) showed that LCA can support structural optimization by linking life-cycle impacts to material selection and design modifications. However, they emphasized that its time- and data-intensive nature restricts practical sustainability-driven optimization to only a small number of alternatives, leaving limited guidance for identifying structurally efficient and environmentally

preferable solutions using performance-based indicators such as capacity-to-GWP ratios. This limitation is most critical during conceptual design, when fundamental decisions on building layout, member geometry, and material classes are made. These early assumptions heavily influence environmental outcomes, yet full LCAs are typically carried out only after the structural design is largely fixed (Hollberg and Ruth 2016). Reinforced-concrete design further complicates early-stage decisions because Eurocode 2 provides a wide range of concrete strength classes—from normal to high and ultra-high performance—that differ not only in mechanical capacity but also in embodied GWP, even within the same nominal grade. Evaluating only a small subset of these options introduces uncertainty and may obscure more sustainable alternatives.

Because early-stage LCA is difficult to apply systematically when many geometry and material combinations must be considered, the methodology proposed in this paper is intended as a pre-LCA decision-support tool. It quantifies the embodied CO_2 implications of early choices—such as strength class and cross-sectional dimensions—that ultimately shape final LCA results. While not a substitute for a full LCA, the method integrates structural performance criteria with environmental indicators to guide the preliminary selection of viable alternatives. A detailed LCA can then focus on a smaller set of well-justified configurations. In this way, the approach supports more informed early design decisions already at the conceptual stage and facilitates broader, more practical integration of LCA into everyday structural engineering workflows.

1.2. Current and future methodology trends for decarbonisation

1.2.1. Performance-Driven Structural and Material Optimisation

Recent research has shown that substantial reductions in the carbon footprint of reinforced-concrete structures can be achieved when structural design choices are systematically linked with material optimisation. Hafez et al. (2024) demonstrated this through a parametric study on a modular mid-rise reinforced-concrete building, evaluating 288 alternatives that varied in slab system, span length, reinforcement detailing, and concrete strength class. Their results highlighted that coordinated design and material optimisation can yield significant emission reductions—approximately 20 % through the adoption of waffle slabs, an additional 20 % through span adjustments, and up to 7 % through reinforcement detailing—with the lowest embodied CO_2 associated with C30/37 concrete. Complementary insights were provided by Nouri et al. (2025), who compared structures designed with C20/25 and C25/30 concretes using pushover analysis. Their cradle-to-gate LCA confirmed a direct link between structural capacity and environmental impact: the lower-strength alternative exhibited over 20 % lower base-shear capacity and roughly 30 % higher environmental impact.

Parallel methodological developments within LCA research stress the need for performance-oriented functional units to ensure meaningful comparison across design alternatives. Traditional volume- or mass-based functional units (e.g., 1 m^3 of concrete) overlook differences in strength, stiffness, and durability, leading to inconsistent or misleading conclusions (Hafez et al., 2019). Systematic reviews show that such normalisation fails to reflect variations in mechanical performance or service life, particularly across different concrete strength classes. To address this, functional units should incorporate performance criteria—such as compressive strength, load-bearing capacity, or design service life—so that material quantities and cross-sectional dimensions emerge from structural demands rather than arbitrary assumptions (Backes et al., 2023). Embedding performance constraints ex ante improves functional equivalence between alternatives and strengthens the robustness and interpretability of subsequent LCA results.

1.2.2. Ex ante decision-support tool prior to LCA

Despite the widespread use of LCA in sustainable building design, a key limitation persists in structural engineering practice: concrete strength classes and member geometries are typically fixed early in the design process, long before LCA is conducted, and without explicit justification based on structural performance or environmental optimisation. Numerous studies show that such early assumptions strongly influence LCA outcomes, while opportunities for meaningful design adjustments diminish rapidly as the project progresses (Hollberg and Ruth, 2016; De Rosa et al., 2018). To address this, recent

LCA methodology emphasises ex ante approaches, in which fundamental design parameters are defined prior to inventory modelling (Buyle et al., 2019; Arvidsson et al., 2024). In an ex-ante framework, structural performance governs the derivation of material quantities and cross-sectional dimensions, ensuring functional equivalence across alternatives and strengthening the robustness of resulting environmental assessments.

The methodology developed in this study implements such an ex-ante decision-support step for reinforced concrete beams. It introduces performance-based pre-design charts that relate bending-moment demand, concrete strength class, CO_2-optimal member depth, and resulting embodied emissions. These relationships are derived from Eurocode-compliant cross-sectional design and an optimisation procedure that minimises A1–A3 embodied CO_2 while satisfying flexural performance requirements. By deriving geometry and reinforcement needs directly from structural performance—rather than from assumed volumes—the approach improves functional equivalence between design options and meets key requirements of structural and building LCA standards (ISO 14044; ISO 21930; EN 15978). The resulting charts allow designers to assess trade-offs between structural capacity, material efficiency, and environmental impact at the conceptual stage, positioning environmental performance as an active design variable rather than a post-design evaluation metric. The framework is fully aligned with performance-based design principles promoted within fib and the development of the Next Generation Eurocode 2, and provides a transparent, reproducible basis for sustainability-oriented conceptual design of reinforced concrete structures.

2. Methodology

2.1. Scope and Assumptions

The methodology is developed for reinforced-concrete beams primarily subjected to bending at the stage of conceptual design. The scope is in the current phase of the project limited to simply supported members under uniformly distributed gravity loads, represented by a design bending moment that includes permanent and variable actions according to standard combinations. Structural verification follows the flexural design rules of the Eurocode 2 (EN 1992-1-1, 2004), including its material models and partial safety factors (γ_S=1.15, γ_C=1.5). Although bending governs the optimization, a representative stirrup configuration is included to account for the embodied CO_2 contribution of transverse reinforcement, even though shear resistance is not treated as an optimization parameter. Embodied CO_2 is assessed for concrete and reinforcing steel using cradle-to-gate (A1–A3) emissions and expressed per meter of beam length. Economic aspects and other environmental indicators are not considered, as the aim is to provide a transparent and practical pre-design tool suitable for early-stage decision-making. These assumptions reflect typical conceptual-design conditions and ensure clarity and reproducibility.

2.2. Input Parameters

The methodology relies on defined structural, material, and environmental inputs. Concrete strength class is treated as a discrete variable, ranging from normal- to high-strength concretes (up to C90/105), each evaluated independently. Beam geometry is described by width and overall depth, with a constant effective cover of 50 mm to the centroid of the tensile reinforcement $c+\phi_c+\phi_{st}/2=50$ mm. For each combination of bending moment and concrete class, the beam depth is determined through the optimization, while longitudinal reinforcement is obtained from Eurocode-compliant sectional equilibrium, subject to minimum and maximum reinforcement ratios.

Environmental performance is evaluated using region-specific A1–A3 embodied CO_2 factors derived from Environmental Product Declarations and national datasets. Concrete GWP values follow the Austrian CO_2 classification system (ÖBV 2025), based on 496 representative mix designs from Austrian ready-mixed and precast producers. For each strength class, the reference GWP is determined using harmonized CEM I-equivalent binder compositions and EN 15804/EN 16757 rules, including typical transport and production emissions. These values provide statistically grounded national references for conceptual design, available up to class C50/60. For higher concrete classes, where national datasets are not available, GWP values are obtained through controlled extrapolation of the ÖBV trend, reflecting

increasing binder content and composition changes. These extrapolated values ensure continuity with national data and are used solely for parametric comparison rather than to represent market averages.

Reinforcing-steel emissions use Austrian EPD values for electric-arc-furnace steel manufactured from 100 % recycled scrap and renewable electricity (Marienhütte 2025), with a representative cradle-to-gate GWP of 293 kg CO_2-eq per ton. This value reflects current low-carbon Austrian steel production (Marienhütte 2025) and is suitable for conceptual-design assessments.

Table 1. Concrete Classes and Corresponding CO_2 emissions.

Properties	C20	C25	C30	C35	C40	C45	C50	C55	C60	C70	C80	C90
f_{ck} (MPa)	20	25	30	35	40	45	50	55	60	70	80	90
f_{cd} (MPa)	13.3	16.7	20.0	23.3	26.7	28.8	30.9	33.0	34.9	38.7	42.3	45.8
f_{ctm} (MPa)	2.21	2.56	2.90	3.21	3.51	3.80	4.07	4.21	4.35	4.61	4.84	5.04
ε_{cu3} (‰)	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.1	2.9	2.7	2.6	2.6
GWP	209	237	250	275	294	307	314	339	353	381	407	431

2.3. Functional unit and derivation of embodied CO_2 intensity

To enable consistent comparison between alternative beam configurations, a performance-based functional unit is adopted. The functional unit is defined as one meter length of reinforced concrete beam designed to resist a specified design bending moment in accordance with Eurocode requirements. This definition reflects the intended structural function at the conceptual design stage and allows direct comparison of alternative combinations of concrete strength class, cross-sectional geometry, and reinforcement content. For each beam configuration, the embodied CO_2 intensity per meter length is calculated as the sum of the contributions from concrete and reinforcing steel, considering life-cycle stages A1–A3. The contribution of concrete is obtained from the concrete volume per meter length of beam multiplied by the corresponding embodied CO_2 emission factor per unit volume for the selected strength class. The contribution of reinforcing steel is determined from the mass of longitudinal and transverse reinforcement per meter length multiplied by the adopted steel emission factor per unit mass. Mathematically, the embodied CO_2 intensity per meter length of beam is expressed as:

$$CO_{2beam} = V_c \cdot GWP_c + m_s \cdot GWP_s \quad (1)$$

where V_c is the concrete volume per meter of beam, GWP_c is the embodied CO_2 emission factor of concrete (kg $CO_{2\text{-}eq}/m^3$), m_s is the mass of reinforcing steel per meter of beam, and GWP_s is the embodied CO_2 emission factor of reinforcing steel (kg $CO_{2\text{-}eq}$/kg). This functional unit ensures that environmental performance is evaluated on the basis of equivalent structural function rather than material quantity alone, and it provides a direct link between structural design decisions and embodied CO_2 emissions at the conceptual design stage. The contribution of reinforcing steel to the embodied CO_2 emissions is calculated on a mass basis, using the reinforcement area determined from structural design and a constant steel density, rather than on a volumetric basis.

2.4. Optimization procedure

2.4.1. Problem Definition

For each target design bending moment M_{Ed} and each concrete strength class $c \in C$ (C20/25, C30/37, …), the objective is to determine the beam configuration that minimizes embodied CO_2 per meter of length while satisfying all Eurocode-compliant flexural design requirements. The concrete strength class is treated as a discrete design option, whereas geometric dimensions remain continuous within predefined limits. The inputs to the problem include the bending moment M_{Ed}, the beam width b (fixed for each chart), and an effective cover c_{eff}=50 mm measured to the centroid of tensile reinforcement. Material parameters and partial safety factors follow the provisions of the Eurocode 2, while embodied-CO_2 factors for concrete (A1–A3) are taken from Austrian national reference data (ÖBV) and for reinforcing steel (A1–A3) from Austrian EPDs. Within this framework, the primary design variable is the overall beam depth $h \in [h_{min}, h_{max}]$, and for each concrete class $c \in C$ the effective depth is determined as $d = h - c_{eff}$.

The required longitudinal reinforcement area A_s is obtained by sectional equilibrium for each pair of (h, c). Additional internal quantities —namely the neutral-axis depth x, compressive and tensile forces F_c and F_s, lever arm z, reinforcement demand, and strain state—are all determined through the Eurocode design checks that ensure structural admissibility.

2.4.2. Objective function (embodied CO_2 per meter)

The functional unit is 1 m of beam spanning in the longitudinal direction and designed for M_{Ed}. The total embodied CO_2 intensity per meter is:

$$J(h,c) = V_c \cdot GWP_c(c) + m_{s,long}(h,c) \cdot GWP_s + m_{s,tr}(h,c) \cdot GWP_s \quad (2)$$

with $V_c(h)=bh\cdot 1m$ [m^3/m], GWPc(c) in [kg CO_2-eq/m^3] and GWPs in [kg CO_2-eq/kg]. The steel mass terms (per meter) are:

$$m_{s,long} = A_s \cdot \rho_s \qquad and \qquad m_{s,tr} = \frac{l_{stir}(h) \cdot A_{stir} \cdot a_{hooks}}{s_{stir}} \cdot \rho_s \quad (3)$$

where ρ_s=7850 kg/m^3; $A_{stir}=\pi\phi_{stir}^2/4$; s_{stir} is stirrup spacing; $\alpha_{hooks}\approx 1.10$ accounts for anchorage legs; and $\ell_{stir}(h)\approx 2(b-2c_{eff})+2(h-2c_{eff})$ is the closed-stirrup length. A representative stirrup scheme (e.g., closed Ø8 @ 200 mm) is adopted to reflect realistic A1–A3 emissions from transverse reinforcement; stirrups are not an optimization variable. The contribution of transverse reinforcement is calculated by multiplying the mass of a single closed stirrup by the number of stirrups per meter length of beam, defined as the inverse of the stirrup spacing.

2.4.3. Structural model (Eurocode-compliant checks)

For each (h,c), the tensile steel area A_s is determined so that the design moment resistance meets the demand. A rectangular stress block with coefficients λ(c), η(c) per EC2 is used:

- Stress block force and lever arm

$$F_c = n \cdot f_{cd} \cdot b \cdot \lambda \cdot x, \quad z = d - \frac{1}{2}\lambda \cdot x \quad (4)$$

- Equilibrium and strength

$$F_c = F_s = A_s \cdot f_{yd}, \quad M_{Rd} = F_c \cdot z \geq M_{Ed} \quad (5)$$

- Reinforcement limits and strain

$$A_{s,min} \leq A_s \leq A_{s,max}, \qquad \varepsilon_s \geq \varepsilon_{sy} = f_{yd}/E_s \quad (6)$$

with $A_{s,min} = max\{0.26\, f_{ctm}/f_{yk}\,, 0.0013\} \cdot b \cdot d$, $A_{s,max} = 0.04bh$, *and* f_{ctm} per strength class. These checks ensure code compliance while leaving h free to move towards lower CO_2.

2.4.4. Optimization statement

For each specified design bending moment and for each selected concrete strength class, the optimization procedure seeks the beam configuration that results in the lowest embodied CO_2 emissions per meter length while fully satisfying the structural requirements prescribed by Eurocode 2. The concrete strength class is treated as a discrete design alternative, whereas the beam height is treated as a continuous design variable within predefined lower and upper bounds. For a given concrete class, candidate beam heights are systematically explored. For each height, the effective depth is determined from the assumed concrete cover and reinforcement detailing, and the corresponding internal force equilibrium is established using the Eurocode-compliant stress block model. The required longitudinal reinforcement area is derived from force equilibrium between concrete in compression and steel in tension. Only configurations that satisfy moment resistance requirements, minimum and maximum reinforcement ratios, and the steel yield strain condition are retained as structurally feasible solutions.

Among all structurally feasible solutions for a given concrete class, the configuration that yields the minimum embodied CO_2 emissions per meter of beam length is identified as the environmentally optimal solution for that class. This minimization accounts for the combined contributions of concrete

volume and reinforcing steel mass, including both longitudinal and transverse reinforcement, using cradle-to-gate emission factors. Instead of selecting a single globally optimal beam configuration across all concrete strength classes, the methodology retains the environmentally optimal solution identified for each concrete class individually. For a given bending moment, the resulting set of class-specific optimal configurations is aggregated and presented in the form of parametric pre-design charts. These charts display, for each considered concrete strength class, the beam height and corresponding embodied CO_2 emissions per meter that minimize environmental impact while satisfying Eurocode-compliant structural requirements. By presenting all concrete classes simultaneously, the charts allow designers to directly compare the environmental and geometric implications of alternative material choices at the conceptual design stage. The final selection of beam configuration therefore remains a designer-driven decision, informed by the visual assessment of trade-offs between concrete strength, member depth, reinforcement demand, and embodied CO_2 intensity.

3. Pre-design charts and application examples

3.1. Single-moment illustrative example (C25/30, b=300 mm, M_{Ed}=350 kNm)

To demonstrate how an individual beam configuration is derived within the proposed framework, this section presents a complete EC2-compliant design calculation for a single beam height. The example illustrates the determination of effective depth, neutral axis depth, longitudinal reinforcement area, and the associated embodied CO_2 emissions per meter. The beam has a rectangular cross-section with width b=300 mm and an h=485 mm. With an assumed concrete cover and detailing allowance of 50 mm to the centroid of tensile reinforcement, the effective depth is: d=h−c=h−50. Concrete class C25/30 and reinforcing steel B500 are assumed; E_s= 200 GPa. Stirrups (representative): Ø8 @ 200 mm; hook factor 1.10. The design material parameters according to Eurocode 2 are: $f_{cd}=f_{ck}/\gamma_c=25/1.5=16.7$ MPa and $f_{yd}=f_{yk}/\gamma_s=500/1.15=435$ MPa. For C25/30, the rectangular stress-block parameters are $\lambda=0.8$ and $\eta=1.0$. The design bending moment is M_{Ed}=350 kNm. Using the EC2 rectangular stress block, the compressive force in the concrete, the internal lever arm and moment equilibrium give:

$$F_c = n \cdot f_{cd} \cdot b \cdot \lambda \cdot x, \quad z = d - \frac{1}{2}\lambda \cdot x, \quad M_{Ed} = F_c \cdot z = n \cdot f_{cd} \cdot b \cdot \lambda \cdot x \cdot \left(d - \frac{1}{2}\lambda \cdot x\right) \tag{7}$$

The code computes the depth of the neutral axis x=266.4 mm. The longitudinal steel area required is:

$$A_{s,min} \le A_s = \frac{F_c}{f_{yd}} = \frac{1065kN}{435MPa} = 2451\ mm^2 \le A_{s,max} = 0.04 \cdot 300 \cdot 485 = 5820\ mm^2$$
$$A_{s,min} = max\{0.26\, f_{ctm}/f_{yk}\,, 0.0013\} \cdot b \cdot d = 0.0013 \cdot 300 \cdot 435 = 169.65\ mm^2 \le A_s \tag{6}$$

Checks for the minimum and maximum reinforcement and steel strain are also performed.

$$\varepsilon_s = \varepsilon_{cu3} \cdot {}^{(d-x)}/_{x} = 0.0035 \cdot \frac{168.6}{266.4} = 0.00221 \ge \varepsilon_{sy} = f_{yd}/E_s = \frac{435}{200000} = 0.00218$$

The embodied CO_2 per meter (A1-A3) are then computed:

$$CO_2 = V_c \cdot GWP_c(c) + m_{s,long}(h,c) \cdot GWP_s + m_{s,tr}(h,c) \cdot GWP_s$$
$$= 0.1455 \cdot 237 + 19.24 \cdot 0.293 + 2.39 \cdot 0.293 = 40.86\ kg\ CO_2/m \tag{2}$$

This single calculation corresponds to one point on Figure 1; evaluating the same EC2-consistent relations across admissible heights gives the complete CO_2 vs height curve, and its minimum. The curve for b=300 mm starts at the minimum admissible height h_{min}= 485 mm; at this boundary the total embodied emissions are 40.86 kg CO_2/m. The class-specific CO_2-optimal point coincides with this boundary for this case, i.e. h^*=485 mm with As^*=2451 mm², x^*=266.42 mm, d^*=435 mm, and M_{Rd}=350.00 kNm. In other words, the environmentally best admissible solution for C25/30 at 350 kNm occurs at the minimum EC2-valid depth (the curve rises for larger h because added concrete volume dominates the modest steel saving under Austrian factors). Correspondingly, Figure 1(a) also shows the curve for b = 400 mm, where the same trend is visible but at consistently higher CO_2 intensities. The

wider section produces uniformly higher emissions because the concrete volume increases with width, while the attainable reduction in height is relatively small.

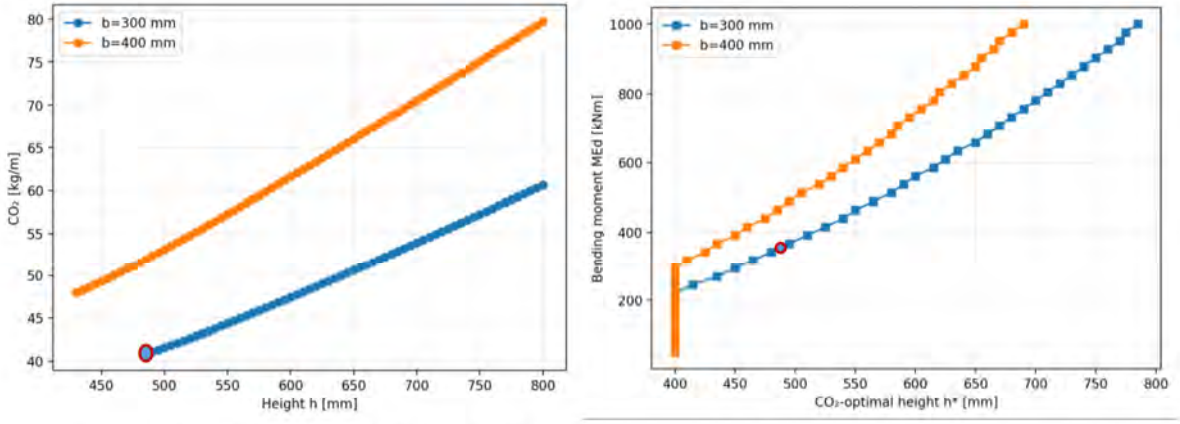


Figure 1. (a) CO_2 vs height for C25/30 – M_{ed}=350 kNm – All EC2 admissible sections, and (b) Bending moment vs CO_2-optimal beam height for C25/30

3.2. CO2-optimal beam height as a function of bending moment (single concrete class)

Building on the single-moment example, the same Eurocode-compliant procedure is next applied to a range of design bending moments for a fixed concrete strength class. In this subsection, concrete class C25/30 and beam width b=300 mm are retained, while the bending moment M_{Ed} is varied within a representative range relevant for reinforced concrete beams in building structures. For each bending moment, the full set of Eurocode-admissible beam sections is generated by solving moment equilibrium exactly for all feasible beam heights and applying the reinforcement and ductility checks of Eurocode 2. The corresponding embodied CO_2 emissions per meter of beam length are evaluated for life-cycle stages A1–A3. From the resulting CO_2–height curve, the class-specific environmental optimum is identified as the beam height that minimises embodied CO_2 for that bending moment. Repeating this procedure for all considered moments yields a single continuous relationship between bending moment and CO_2-optimal beam height, denoted $h^*(M_{Ed})$, as shown in Fig. 1 (b).

Figure 1b presents the resulting curve for concrete class C25/30. The curve reflects the combined influence of structural demand and material efficiency. At lower bending moments, the CO_2-optimal height coincides with the minimum Eurocode-admissible depth identified in Section 3.1. As the bending moment increases, the minimum admissible depth shifts to larger values and the CO_2-optimal height increases accordingly. This progression captures, in a compact form, how increasing flexural demand translates into larger member depths when environmental impact is minimised under consistent structural constraints.

Importantly, the curve in Figure 1(b) does not represent a unique "best" design across material choices, but rather the best achievable beam height within a single concrete class. It therefore isolates the influence of bending moment on geometry and embodied CO_2 without conflating it with changes in concrete strength. This class-specific optimal-height curve forms the basis for the next step of the analysis, in which the same relationship is generated for multiple concrete strength classes and synthesised into the pre-design charts presented in Section 3.3.

3.3. Multi-class pre-design charts

The final step of the methodology extends the class-specific optimization described in Section 3.2 to the full set of considered concrete strength classes and to both investigated beam widths (300 mm and 400 mm). For each width, the optimization procedure is repeated across all concrete strength classes and the full range of bending moments. At each moment, the embodied CO_2 emissions are minimized over all Eurocode-admissible depths, thereby yielding a class-specific CO_2-optimal depth h^*. Figure 2 presents the resulting dual-panel pre-design charts for b=300 mm and b=400 mm. Both panels use the CO_2-optimal depth h^* as the horizontal axis, thereby providing a more transparent basis for comparison between design alternatives.

The upper panel shows how the optimal member depth increases with the bending-moment demand for each strength class. For a fixed depth, differences between classes reveal how higher-strength concretes can carry larger bending moments for the same geometric envelope. The lower panel shows the embodied CO_2 that corresponds to the same optimal depth h^*. Once a designer selects a candidate depth on the horizontal axis, the chart directly reveals the resulting CO_2 intensity for each class. This formulation makes CO_2 consequences of geometric choices explicit, while ensuring that only structurally admissible solutions are compared. For any chosen depth h^*, the chart immediately shows whether a higher-strength class leads to lower or higher embodied CO_2. At small depths, differences between classes tend to be modest because all classes operate near their minimum admissible depth.

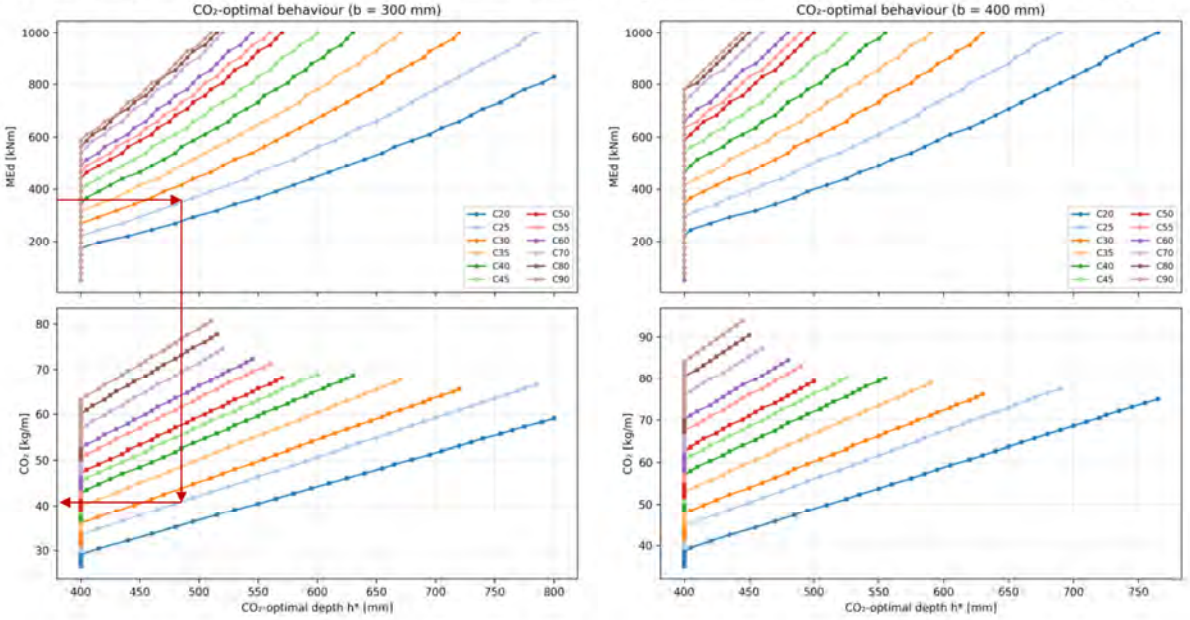


Figure 2. (top) Bending moment and (bottom) CO_2 vs optimal beam height for all concrete classes

At conceptual stage, a designer can select the target M_{Ed} on the vertical axis of the top panel, scan horizontally to the class of interest, and read the optimal depth h^*. If multiple classes are acceptable for the project, the designer can compare the heights at the same moment across curves (top panel) and then follow each point down to the bottom panel to compare the CO_2 consequences of those class-specific optima. Because the same beam width, detailing, and verification rules are used for every class, the comparison is functionally equivalent.

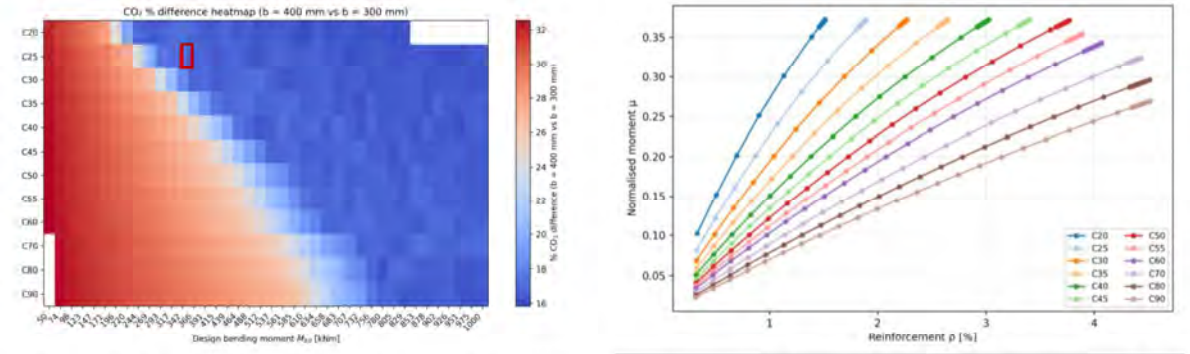


Figure 3. CO_2 % difference by class and M_{Ed} (400 mm vs 300 mm) (left) and $\mu=M_{Ed}/(bd^2f_{cd})$ vs $\rho=A_s/(bd)$ for b=300 mm (right)

The CO_2 difference heatmap demonstrates that reducing beam width is consistently more effective than modifying concrete strength class in lowering embodied emissions, because concrete volume scales directly with width while the resulting reduction in optimal depth remains relatively small. Since concrete dominates A1–A3 impacts and reinforcing steel contributes only marginally to total emissions,

the 33 % increase in width from 300 mm to 400 mm produces a systematic CO_2 penalty across all bending-moment levels, with differences ranging from about 30 % at low MEd to roughly 16–18 % at higher M_{Ed}. This penalty is not compensated by the modest depth savings enabled by the wider section. Consequently, selecting the minimum structurally admissible beam width is an effective early-stage decarbonization strategy, as width reductions yield immediate and robust CO_2 savings without requiring significant changes in depth or reinforcement demand.

The relationship between the normalized bending moment and the corresponding longitudinal reinforcement ratio at the CO_2-optimal depth provides a compact, performance-based view of the reinforcement demand across concrete strength classes. As shown in Figure 3, the curves for all classes exhibit a smooth, consistently increasing relationship between ρ and μ, illustrating that—once geometric efficiency has been optimized—additional moment demand is primarily accommodated by increasing tensile steel rather than by large changes in depth. Higher-strength concretes consistently require lower reinforcement ratios at the same μ-level, reflecting their higher compressive capacity and the resulting ability to mobilize a larger lever arm at similar efficiency states.

4. Discussion

The CO_2-optimal charts developed in this study reveal several important relationships between structural demand, concrete strength class, beam geometry, and embodied CO_2. For lower bending moments, the CO_2-optimal depths of all concrete classes cluster near the minimum admissible section depth. In this region, differences in A1–A3 emissions between classes are primarily driven by the GWP of the concrete itself, since both depth and reinforcement demands are relatively small. As a result, lower-strength concretes such as C25/30 and C30/37 consistently exhibit lower embodied CO_2 than higher-strength classes. In this regime, the potential for environmental improvement through material strength selection is modest, and class changes do not significantly affect CO_2 performance.

As bending-moment demand increases, the optimal depth required for lower-strength concretes rises more rapidly than for higher-strength classes. This geometric penalty leads to substantially increased concrete volume per meter, which dominates total CO_2 emissions in the Austrian context where reinforcing steel has very low A1–A3 impact. Consequently, at medium to high bending moments, higher-strength concretes begin to outperform lower-strength alternatives in total embodied CO_2. This effect becomes progressively more pronounced as moment demand approaches the upper range of the charts, where only the higher-strength classes remain feasible within the 800 mm depth limit.

The role of beam width is highlighted by the CO_2 %-difference heatmap between 300 mm and 400 mm beams. For all concrete classes and bending-moment levels, the wider beam results in higher CO_2 per meter. This is because concrete volume, which dominates embodied emissions, increases directly with width, while the corresponding reduction in optimal depth is insufficient to compensate for the additional concrete volume. The extremely low A1–A3 emission factor of a representative Austrian reinforcing steel further diminishes the relative influence of steel mass changes. This behaviour underscores an important practical conclusion: within the examined ranges, minimizing beam width is a highly effective strategy for reducing embodied CO_2, particularly during early-stage decision-making when cross-section selection is still flexible.

5. Conclusions

This study introduced CO_2-oriented pre-design charts that link bending-moment demand, concrete strength, and beam geometry under Eurocode-compliant constraints. The charts make it possible to identify environmentally favourable beam configurations early in the design process, before undertaking a full LCA. The results show that CO_2 performance is governed primarily by geometric efficiency and concrete volume, while steel has only a minor influence under low-emission production conditions. Within realistic limits on depth and minimum concrete class, the charts reveal how optimal depths evolve with structural demand and when higher-strength concretes become environmentally competitive. Across all investigated cases, beam width has a consistently strong effect on embodied CO_2, with narrower beams reliably offering lower emissions for the same structural capacity. Overall,

the proposed workflow provides a practical, transparent tool that helps designers quickly narrow the design space to structurally admissible and environmentally efficient solutions during the conceptual stage. Moreover, the methodology is directly transferable to other geographical contexts: by substituting region-specific emission factors and adapting the limited code-dependent parameters, the same optimization framework can be applied under different concrete standards and material datasets without loss of generality.

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References

Anderson, J., and Moncaster, A. (2020). Embodied carbon of structural systems: A performance-based comparison. Structural Engineering International, 30(2), 1–10.

Arvidsson, R., Svanström, M., Sandén, B. A., Thonemann, N., and Steubing, B. (2024). Terminology for future-oriented life cycle assessment: Review and recommendations. The International Journal of Life Cycle Assessment, 29, 607–613.

Backes, J. G., Hinkle-Johnson, R., and Traverso, M. (2023). The influence of the functional unit on the comparability of life cycle assessments in the construction sector: A systematic literature review and attempt at unification for reinforced concrete. Case Studies in Construction Materials, 18, e01966.

Barbhuiya, S., and Das, B. B. (2023). Life cycle assessment of construction materials: Methodologies, applications and future directions for sustainable decision-making. Case Studies in Construction Materials, 19, e02326.

Buyle, M., Braet, J., and Audenaert, A. (2019). The future of ex-ante life cycle assessment? Lessons learned and perspectives. Journal of Cleaner Production, 214, 617–629.

de Paula Filho, J. H. M., D'Antimo, M., Charlier, M., and Vassart, O. (2024). Life-cycle assessment of an office building: Influence of the structural design on the embodied carbon emissions. Modelling, 5(1), 55–70.

De Rosa, M., Pizzol, M., and Schmidt, J. (2018). How methodological choices affect LCA climate impact results: The case of structural timber. The International Journal of Life Cycle Assessment, 23(1), 147–158.

EN 15804:2022. Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products. CEN, Brussels.

EN 15978 (2011). Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method. CEN, Brussels.

EN 16757:2023. Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements. CEN, Brussels.

EN 1992-1-1 + AC2:2010 (2004). Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings. CEN, Brussels.

EN 206:2021. Concrete – Specification, performance, production and conformity. CEN, Brussels.

Hafez, H., Kurda, R., Cheung, W. M., and Nagaratnam, B. (2019). A systematic review of the discrepancies in life cycle assessments of green concrete. Applied Sciences, 9(22), 4803.

Hafez, H., Bajić, P., Aidarov, S., et al. (2024). Parametric study on the decarbonization potential of structural system and concrete mix design choices for mid-rise concrete buildings. Materials and Structures, 57, 85.

Hollberg, A., and Ruth, J. (2016). LCA in architectural design – A parametric approach. The International Journal of Life Cycle Assessment, 21(7), 943–960.

ISO 14044 (2006). Environmental management — Life cycle assessment — Requirements and guidelines. International Organization for Standardization, Geneva.

ISO 21930 (2017). Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services. International Organization for Standardization, Geneva.

Lützkendorf, T. (2018). Assessing the environmental performance of buildings: Trends, lessons and tensions. Building Research & Information, 46(5), 594–614.

Nouri, Z., Massumi, A., Asadollahfardi, G., et al. (2025). Structural and environmental impacts of concrete quality: A comparative life cycle assessment. Scientific Reports, 15, 16257.

ÖBV (2025). CO_2 Classes for Concrete. Guideline of the Austrian Association for Construction Technology (Österreichische Bautechnik Vereinigung), Vienna, March 2025.

Stahl- und Walzwerk Marienhütte GmbH (2025). BAU–EPD–MARIENHUETTE–2025–1 - ECOINVENT - Baustahl: Environmental Product Declaration. Bau EPD GmbH, Graz, July 2025.