SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V13I4P103

Volume 13 Issue 4, 33-44, April 2026

Original Article

Performance-Based Selection of Concrete Strength Grades in Terms of Embodied Carbon and Economic Efficiency for Structural Elements

Riza Suwondo[1], Made Suangga[1], Militia Keintjem[2], Mohammed Altaee[3]

[1]*Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, Indonesia.*
[2]*Karbonara Research Institute, Jakarta, Indonesia.*
[3]*Environmental Research and Studies Centre, University of Babylon, Iraq.*

[1]*Corresponding Author : riza.suwondo@binus.ac.id*

Received: 05 January 2026 Revised: 05 February 2026 Accepted: 04 March 2026 Published: 28 April 2026

Abstract - *The construction industry, particularly reinforced concrete structures, is one of the largest contributors to global carbon emissions. These high emissions are due to the high embodied carbon content of the primary materials, namely, cement and reinforcing steel. Therefore, in line with efforts to transition to low-carbon construction, improving the material efficiency of structural elements is a top priority that must be implemented immediately. This study focused on assessing the impact of concrete compressive strength on the embodied carbon and cost of RC beams and columns of various dimensions that achieved the same structural performance. Multiple beam and column configurations with four common concrete grades (25, 28, 32, and 35 MPa) were studied. In each case, the steel reinforcement concrete was designed to meet the specified flexural or axial moment capacities so that they could be compared on equal terms. Embodied carbon was calculated for each case using a cradle-to-gate methodology according to BS EN 15978:2011, while the cost analysis was based on direct material quantities. The findings indicated that, for RC beams, stronger grades of concrete increased the cost and embodied carbon without significantly increasing the structural capacity, particularly in larger sections. The most sustainable and cost-effective solution involves the use of low-strength concrete and more compact beam sections. However, the size and strength of RC columns have the advantage of reducing the amount of reinforcement, and consequently, the embodied carbon and cost. Sensitivity analysis confirmed the robustness of these trends, particularly the predominant impact of steel on columns and concrete for beams. The study concluded that choosing the optimal concrete strength should consider the element and geometry: lower grades should be assigned to beams, while higher grades should be reserved for compression-dominated columns. The results assist in the practical determination of sustainable materials for structural design while also defending performance-based, economically effective, and cost-efficient RC construction.*

Keywords - *Embodied carbon, Reinforced concrete, Cost optimisation, Sustainable design, Built environment.*

1. Introduction

The built environment is under pressure to reduce its negative impacts, especially when it comes to the construction and use of buildings and infrastructure [1]. The construction sector consumes a large amount of energy and contributes significantly to greenhouse gas emissions, thereby rapidly driving climate change [2]. Concrete is the most widely used construction material in built environments. Its availability, durability, and versatility make it a preferred material for structural applications. However, the environmental costs of concrete are significant. Cement, which binds concrete and is its primary source of embodied carbon, is responsible for 8% of the global CO_2 emissions [3,4]. Thus, climate emergencies are a strong motivator for the construction and concrete industries to pursue net-zero emissions.

The evaluation and optimisation of a building's environmental impact now include embodied carbon as one of the most important metrics. This includes the carbon footprints of the extraction and processing of raw materials, manufacturing, transportation, construction, operation, maintenance, and final disposal [5–7]. The BS EN 15978 standard [8] regulates the lifecycle environmental assessment by separating the emissions into different stages. The relevant one is 'Product', stages 'A1 to A3', which include emissions produced by the extraction of raw materials, transportation, and manufacturing, the 'cradle-to-gate' phase. Many case studies [9–13] have reported that this phase contributes approximately 70 to 90% of the total lifecycle embodied carbon of the building. In support of these assessments, the Inventory of Carbon and Energy [14] database provided standard 'cradle-to-gate' embodied carbon coefficients for various construction materials. This allows for the determination of total embodied carbon, which is a vital metric for understanding and refining structural design for environmental purposes.

Recent studies on embodied carbon reduction in reinforced concrete structures can be classified into three main categories. The first group focuses on the system-level optimisation of entire building frames using metaheuristic algorithms or parametric modelling approaches. For example, Kaveh et al. [15] applied evolutionary algorithms to minimise cost and CO_2 emissions in reinforced concrete frames, while Eleftheriadis et al. [16] integrated BIM-based optimisation to balance structural performance and environmental impact. These studies demonstrate that structural optimisation can significantly reduce carbon emissions; however, they primarily evaluate global system behaviour rather than the influence of specific design parameters at the element-level scale.

Other studies in this group examine alternative materials and hybrid systems. Bechmann and Weidner [17] showed that material substitution, such as in wood-concrete hybrid structures, has the potential to reduce carbon emissions. Similar studies on supplementary cementitious materials and low-carbon concrete have also demonstrated end-to-end emission reductions. However, this approach still leaves a research gap: no one has explicitly measured how conventional design choices, such as variations in concrete compressive strength, interact with reinforcement requirements and their impact on embodied carbon holistically.

The third category focuses on optimising individual structural components by adjusting the geometric dimensions and reinforcement requirements. This approach aims to improve efficiency without changing the underlying materials used. For example, Goodchild et al. [18] developed economic design charts for reinforced concrete slab systems based on Eurocode provisions, demonstrating how span-to-depth ratios and reinforcement levels influence cost efficiency. Meanwhile, Trinh et al. [19] took this approach to a more advanced level by proposing a carbon optimization framework for flat slab buildings. By utilising artificial neural networks, they were able to predict optimal design solutions and highlight the influence of geometric parameters and reinforcement requirements on the overall carbon footprint.

Considerable progress has been made in optimising structural systems and alternative materials to reduce embodied carbon in reinforced concrete construction. However, most existing studies focus on whole-building or system-level optimisation, with limited attention to the influence of fundamental design parameters at the structural-element scale. In particular, the effect of concrete compressive strength on the reinforcement demand, embodied carbon, and construction cost of individual beams and columns remains insufficiently quantified.

In practice, concrete strength selection is typically driven by structural or code requirements without explicit evaluation of its environmental and economic trade-offs. While higher-strength concrete increases the embodied carbon per unit volume, it may reduce the reinforcement demand, particularly in compression-dominated members. Conversely, in flexure-dominated members, reinforcement governs the capacity, and increasing concrete strength may provide limited structural benefits while increasing carbon intensity and cost. Despite this mechanical distinction between beams and columns, the integrated relationship between concrete strength, reinforcement requirements, embodied carbon, and cost at the element level has not been examined systematically.

Therefore, this study adopted a performance-based framework to evaluate the reinforced concrete beams and columns designed to achieve equivalent structural capacity using different concrete grades (25–35 MPa). The novelty of this research lies in isolating the concrete compressive strength as the governing design variable at the member level while simultaneously quantifying the embodied carbon and direct material cost. By explicitly distinguishing between flexure-dominated and compression-dominated behaviours, this study provides practical and element-specific guidance for sustainable material selection beyond system-level optimisation approaches.

2. Methodology

This study aims to analyse the cost and embodied carbon of flexural reinforcement design ramifications for RC (reinforced concrete) beams and columns. This study accounted for the different strengths of concrete and considered four different compressive strength grades: 25, 28, 32, and 35 MPa. For each grade, the required amount of flexural reinforcement was calculated such that all design cases met the same nominal flexural or axial strength. This approach ensures that the evaluation is conducted based on equivalent performance, so that any differences in material quantities can be objectively justified. The value assessment focuses on two main parameters: embodied carbon and construction costs, with the aim of identifying the optimal concrete quality that balances the economic and environmental aspects.

2.1. RC Beam Design

The design of the RC beam in this study was conducted with reference to SNI 2847:2019 [20], which was adapted from ACI 318-19 [21]. For the beam, it was assumed to have only a singly reinforced rectangular section, where only tension reinforcement was provided to counter the flexural demand, and compression reinforcement was neglected. These assumptions reflect the standard practices commonly applied in the design of conventional flexural elements. Thus, they allow for simpler and more consistent comparisons of the reinforcement requirements across different concrete grades.

The nominal flexural strength of the beam section (M_n) was calculated using the following equation.

$$M_n = A_s f_y (d - a/2) \quad (1)$$

Where A_s is the area of the tension reinforcement, f_y is the yield strength of the reinforcement, d is the effective depth of the beam, and a is the depth of the equivalent rectangular stress block, defined as

$$a = \frac{A_s f_y}{0.85 f_c' b} \quad (2)$$

Where f_c' is the compressive strength of the concrete and b is the width of the beam.

Referring to the provisions of SNI 2847:2019, the minimum reinforcement requirements were checked to ensure that the structure avoids the risk of brittle failure while guaranteeing adequate ductility. The minimum area of tension reinforcement is given by

$$A_{s,min} = max\left(\frac{0.25 f_c'}{f_y} bd, \frac{1.4}{f_y} bd\right) \quad (3)$$

This provision ensures that the area of reinforcement provided is not less than the minimum threshold required by the code, so that safe structural performance can be met.

For each variation of the concrete compressive strength considered, the tensile reinforcement area (A_s) was designed such that the beam achieved an equivalent nominal moment capacity (M_n). This approach allows for a consistent comparison between the material efficiency and structural performance.

2.2. RC Column Design

The interaction diagram method was used to determine the design strength of the RC column. This method accounts for the integrated axial and flexural demands of a section. These diagrams provide the limits of the safe combinations of the axial load (P_n) and bending moment (M_n) that the column can resist, considering material nonlinearity, along with the strain compatibility boundary. An interaction diagram was developed by performing a cross-sectional analysis with various assumptions on the neutral-axis depth and capturing the transition from pure axial compression to pure bending, as shown in Figure 1.

The key design points on the interaction diagram include the following.

- Pure axial compression
  When both the concrete and reinforcement are in compression,

$$P_n = (bh - A_s - A_s')0.85 f_c' + A_s f_y + A_s' f_y \quad (4)$$

- Balanced failure condition
  When the concrete strain reaches its maximum (ε_{cu} = 0.003) simultaneously, the tensile steel yields

$$P_n = 0.85 f_c' ab + A_s f_y - A_s' f_y \quad (5)$$

$$M_n = A_s f_y (d - c) + A_s' f_y (c - d') + 0.85 f_c' ab(c - a/2) \quad (6)$$

- Pure bending
  When the axial force was zero, only the flexural moment was resisted by the tensile steel.

$$M_n = A_s f_y (d - a/2) \quad (7)$$

- Pure tension
  When both layers of the reinforcement are in tension

$$P_n = A_s f_y + A_s' f_y \quad (8)$$

Where A_s is the area of the tensile reinforcement, A_s' is the area of the compressive reinforcement, b is the width of the column, h is the total depth of the column, d is the effective depth of the tensile reinforcement, d' is the effective depth of the compressive reinforcement, $a = \beta_1 c$, c is the depth of the neutral axis, and β_1 is defined according to SNI 2847:2019, based on f_c'.

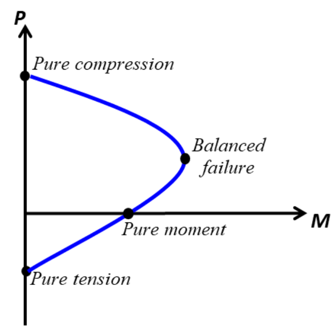

Fig. 1 Interaction diagram of RC column

2.3. Embodied Carbon Calculation

To assess sustainability in construction, one must evaluate the environmental consequences involved in all stages of the lifecycle of building materials. This study follows the guidelines in BS EN 15978:2011[8], which include LCA standards for buildings, emphasising modules A1 to A3. This is the cradle-to-gate stage, which includes the extraction of raw materials, their transportation to the manufacturing facility, and production of materials [22].

The importance of the cradle-to-gate stage has been highlighted in literature. For example, the London Energy Transformation Initiative [23] highlighted that in the case of typical buildings, cradle-to-gate activities could account for as much as 50% of the total lifecycle carbon emissions, while construction activities (Module A5) were typically approximately 5% of the total embodied carbon. This has been confirmed by other case studies [24-26], which observed that 1% to 15% of activities were in construction and transport. Hence, this study, which is intended to analyse the environmental effects of various concrete compressive strengths and reinforcement configurations under a constant construction method, focuses on cradle-to-gate embodied carbon as an indicator of performance. Maintenance and repair activities during use (Module B) have impacts over the lifetime of a building, but the current study focuses on the differences driven by the materials at the level of structural elements, so those activities were excluded. With beams and columns, which usually have long service lives and limited maintenance, this study anticipates that the impact of the use phase will be small or highly dependent on the particular context. The total Embodied Carbon (EC) of each reinforced concrete element (beam or column) was calculated by summing the emissions from its two main constituents, concrete and reinforcing steel. The calculations were performed using the following equation:

$$EC = \sum Q_i CF_i \quad (9)$$

where Q is the quantity of material, and CF is the carbon factor of the material derived from an inventory of carbon dioxide and energy using circular ecology [14], as presented in Table 1. The use of standardised data ensures consistency in carbon accounting and comparability across all design scenarios.

Table 1. Carbon factor value [14]

Material	Carbon factor
Concrete grade fc' 25 MPa	284 $kgCO_2e/m^3$
Concrete grade fc' 28 MPa	301 $kgCO_2e/m^3$
Concrete grade fc' 32 MPa	330 $kgCO_2e/m^3$
Concrete grade fc' 35 MPa	355 $kgCO_2e/m^3$
Rebar steel	1.99gCO_2e/kg

2.4. Cost Analysis

Along with the embedded carbon assessment, this study conducted a cost analysis for each design scenario of the reinforced concrete beams and columns. The goal was to determine the economic effects of different concrete strengths and the corresponding amounts of concrete-reinforcing steel for each scenario. An understanding of the economic trade-offs in this analysis provides a construction budget for carbon cost analysis to create a balanced assessment. The overall cost of a structural element is calculated by aggregating the costs of concrete and reinforcing steel, as follows:

$$Cost = \sum Q_i P_i \quad (10)$$

Where Pi is the unit price of concrete and other construction materials determined from regional construction cost estimations published by the Indonesian Ministry of Public Works, ensuring sectoral alignment. Table 2 summarises the estimations for the construction materials used in this study.

Construction costs are calculated based on direct material and labour quantities, excluding equipment costs, overhead, profit, and other indirect costs. This simplification aimed to isolate the influence of concrete quality and reinforcement requirements on the material cost performance under conditions of equivalent structural capacity. The results are presented per structural element to align with the output of the embodied carbon analysis. However, this approach captures only a portion of the total project cost. External factors, such as reinforcement density, labour productivity, and site conditions, can influence actual field costs. Therefore, the findings of this study are intended as comparative indicators of material efficiency and not as a complete project cost estimate.

Table 2. Material unit price

Material	Unit price (IDR)
Concrete grade fc' 25 MPa	900,000 $/m^3$
Concrete grade fc' 28 MPa	935,000 $/m^3$
Concrete grade fc' 32 MPa	975,000 $/m^3$
Concrete grade fc' 35 MPa	1,040,000 $/m^3$
Rebar steel	10,000 /kg

This study used structural design methods, embodied carbon assessment, and cost estimation based on established standards. The novelty of this study lies in the integration of these methods within a performance-based comparative framework, wherein beam and column elements are designed to achieve equivalent structural capacities across different concrete grades. By isolating the concrete compression grade as the primary variable, this approach allows for a systematic evaluation of its effects on reinforcement requirements, embodied carbon, and cost at the element level.

3. Results and Discussion

3.1. RC Beam

Three beam cross-sectional sizes were evaluated in this study: 60 cm × 30 cm, 80 cm × 30 cm, and 100 cm × 30 cm. These three dimensions were selected because they represent the cross-sectional proportions commonly encountered in beam design practices for a 6 m span. A 100 cm × 30 cm reinforced concrete beam made of 35 MPa concrete and five 16-mm diameter bars, which provided a reinforcement ratio close to the minimum code requirements, was used to determine the nominal flexural capacity of the beam as 386 kNm. To ensure a uniform comparison, the other two section sizes were assessed with varying concrete grades of 25, 28, 32, and 35 MPa, with varying reinforced concrete, so that each design was able to achieve the same flexural capacity as the beam that acted as the benchmark. This is illustrated in Figure 2. All different grades of concrete for each section size were designed successfully to achieve a nominal moment of 386 kNm, which is close to the benchmark. The minor deviations that were noticed were due to the geometric differences that affect the position of the lever arm and the stress block depths and widths. Nonetheless, it was illustrated that adjusting the beams' constituent elements made it possible to maintain comparable performance levels, irrespective of the variations in the beam depth and the strength of the concrete.

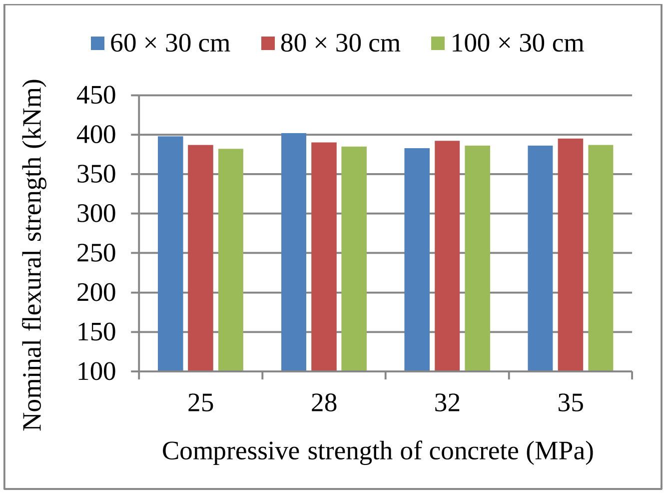

Fig. 2 Flexural strength of RC beam for different concrete grades

Figure 3 illustrates the percentage of the beams' gross concrete cross-sectional area taken by the reinforcement and the results for each combination of the cross-sectional area and concrete grade. The results of each concrete grade combination for each beam section and the overall trend showed that smaller beam sections required a higher reinforcement ratio to achieve the same nominal flexural capacity. Specifically, the 60 × 30 cm section exhibited the highest reinforcement demand, with ratios exceeding 1.2% for all concrete grades.

In contrast, the 100 cm × 30 cm benchmark section achieved the target strength with a much lower reinforcement ratio, remaining approximately 0.34%–0.36% even at lower concrete grades. The 80 cm × 30 cm section produced intermediate values, demonstrating that the reinforcement demand decreased with increasing beam depth for a fixed width and design strength.

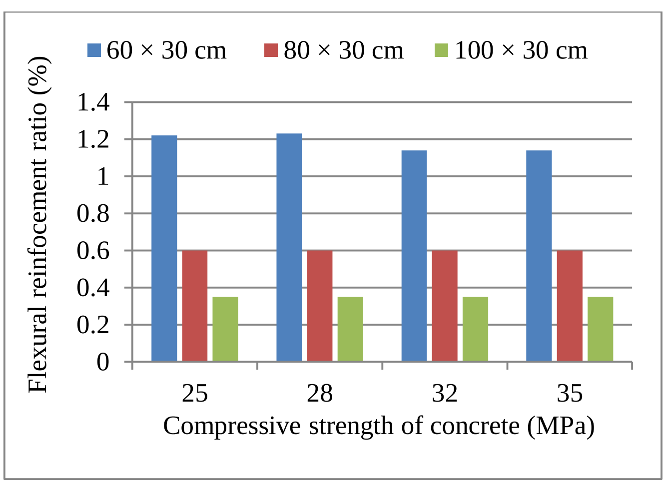

Fig. 3 Reinforcement ratio of RC beam for different concrete grades

For a specific configuration of reinforcement, the grade of concrete has a small influence on the total flexural strength of a singly reinforced rectangular concrete beam, which is probably due to the fact that in flexural design the moment resistance is mostly controlled by the tensile reinforcement in cases where the section is under-reinforced, which leads to the neutral axis being well confined within the section. In this case, an increase in the concrete strength results in an insignificant increase in the contribution of the compressive part, thereby affecting the overall flexural strength of the section to a lesser extent.

Figure 4 displays the total embodied carbon for all beam designs, considering both concrete and reinforcing steel. The results illustrate the effects of the concrete compressive strength, embodied carbon, and section geometry. For every section size, the total embodied carbon accumulated as the compressive strength of the concrete increased. This is due to the high-carbon concrete composition and cement content. While a high concrete strength, owing to compressive capacity enhancement, may slightly reduce the amount of reinforcement needed, the savings on steel emissions do not compare to the emissions from the concrete. Therefore, the 25 MPa concrete grade was consistently correlated with lower carbon values.

The size of the beam section also has a considerable effect on embodied carbon. The 60 × 30 cm section posed the least embodied carbon across all grades of concrete, followed by the 80 × 30 cm and 100 × 30 cm sections. This is primarily because the volume of concrete for smaller sections is less, although the reinforcement ratios are higher to attain the same flexural strength. Although smaller sections require a greater volume of steel, as illustrated in Figure 3, the emission impacts of concrete are primarily a result of the carbon–concrete volume. Although smaller sections require higher reinforcement ratios, their reduced concrete volume results in a lower total embodied carbon.

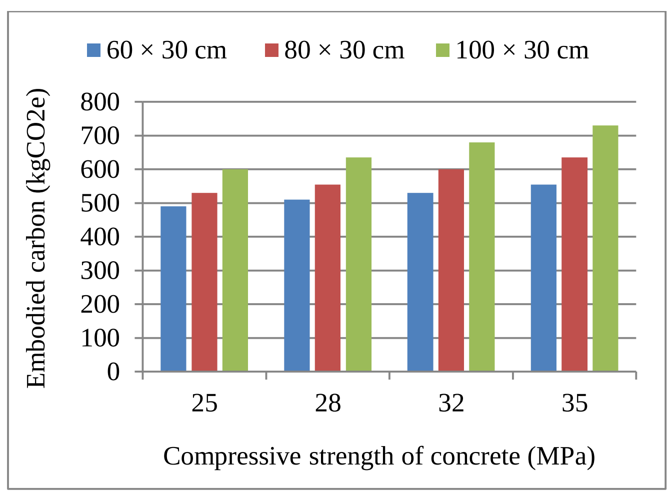

Fig. 4 Total embodied carbon of RC beam for different concrete grades

This illustrates an important point: minimising the volume of concrete used has a greater impact on reducing embodied carbon than marginally reducing carbon from the steel reinforcement added to the structure. While reinforcement might have a greater carbon footprint per weight, the sheer volume of concrete in a beam section means that concrete is mainly responsible for total emissions. This means that designing more sustainable beam sections is possible if smaller section sizes and moderate grades of concrete are used, assuming that the strength and serviceability of the structure are not compromised. This adds to the more general observation that, in addition to material selection, geometric design has a strong influence on structural efficiency and the reduction of embodied carbon. For low-carbon concrete structures, a streamlined design for section dimensions and material grade must be coordinated.

Figure 5 presents the data for the cost analysis of materials for each design of reinforced concrete beams, considering the price of concrete and the cost of the concrete reinforcement. The findings show the relationship between the profile size and the strength of concrete when evaluating the cost performance of beam elements. For the lowest concrete grades, that is, 25 and 28 MPa, the differences in the total cost among the three beam sections were fairly close. This indicates that with lower-strength concrete, the cost balance between reinforced concrete and the volume of concrete (i.e., the cost of concrete) becomes more favourable. Even though the smaller sections, for instance, 60 × 30 cm, require more steel to be added to meet the flexural requirement of the benchmark section, the concrete and reinforcement at these grades are significantly cheaper and reduce the overall cost of the balance.

To investigate the cost information for the constructed beam sections in the 32 and 35 MPa beams, the difference in the cost of the constructed beam sections becomes more noticeable. Within the constructed beam sections, the 100 × 30 cm section consistently incurred the highest cost, whereas the 60 × 30 cm section cost the least. This is owing to the difference in the thicknesses of the beams and the associated costs with high-strength concrete. According to the analysis, high-grade concrete reduces the amount of reinforcements needed in a section, and the finances of the steel that are saved do not outweigh the cost of using high-strength concrete in larger sections because it is in larger volumes.

Economically, these findings indicate that the effect of the section size on cost becomes more significant as the concrete quality increases. For high-strength concrete, reducing the section depth can provide substantial cost savings, provided that the structural and serviceability requirements are met. Conversely, for low-strength concrete, variations in the section size have little impact on the total cost, allowing greater geometric flexibility in the design without significant economic consequences.

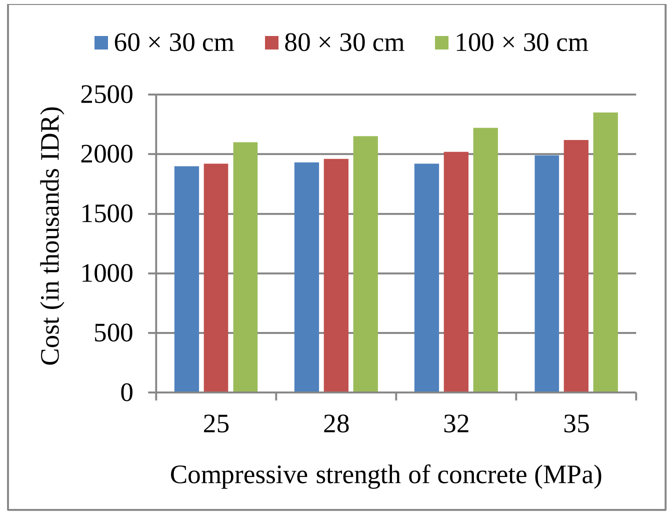

Fig. 5 Total cost of RC beam for different concrete grades

Overall, the results highlight the value of comprehensive cost optimisation, considering both the attributes of the materials and the shapes of the sections, particularly in high-strength concrete contexts. Choosing smaller, more structurally efficient beam sections provides concrete cost savings while achieving, and in some cases exceeding, the expected structural performance.

3.2. RC Column

Two square column sections with heights of 4 m were considered: 60 × 60 cm and 55 × 55 cm. As a benchmark, a 60 cm × 60 cm column with a concrete compressive strength of 35 MPa and a minimum longitudinal reinforcement ratio of 1% was selected. The interaction curve developed for this configuration serves as the reference performance envelope. To ensure comparability, the 55 cm × 55 cm column and other concrete grades (25, 28, and 32 MPa) were analysed by adjusting the reinforcement ratios such that all columns matched the interaction strength of the benchmark.

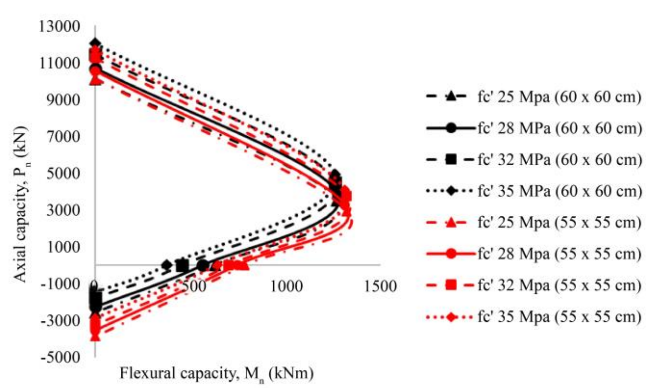

Fig. 6 Interaction diagram of RC column for different concrete grades

Interaction diagrams were generated as shown in Figure 6, illustrating in one view the axial and flexural capacities for the column configuration. These diagrams confirm that all the column design sections of any concrete strength were designed to achieve the given structural performance of the axial-moment capacity. The interaction curves for the 60 cm × 60 cm and 55 cm × 55 cm columns showed comparable results, illustrating the effectiveness of the reinforcement designed for adjusting the varying cross-section and concrete strength around a target mean structural performance.

To maintain balanced axial and flexural strengths across different configurations of columns, the increment of the longitudinal reinforcement must be tailored accordingly. Figure 7 shows the required reinforcement ratios for various concrete grades and column cross-sectional sizes. In general, smaller cross sections require significantly more reinforcement to achieve the same strength as larger cross sections. For example, in 25 MPa concrete, a 55 × 55 cm column requires a reinforcement ratio of more than 3.0%, whereas a 60 × 60 cm column requires only 1.8%. This trend was observed for all concrete grades, confirming that reductions in the cross-sectional size must be compensated for by increasing the steel reinforcement.

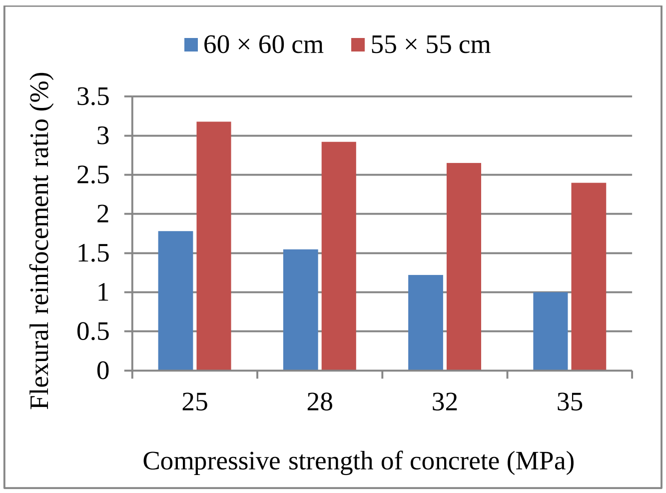

Fig. 7 Reinforcement ratio of RC column for different concrete grades

For both column sizes, the reinforcement ratio decreased as the concrete compressive strength increased. This is understandable because higher-strength concrete can support greater compressive loads, reducing the need for steel. Notably, at 35 MPa, a 60 × 60 cm column achieves the required strength with a minimum reinforcement ratio of 1.0%, whereas a 55 × 55 cm column still requires 2.4%. This demonstrates that the penalty of smaller cross-sectional sizes persists even at higher concrete strengths.

The embodied carbon impacts of various column configurations are shown in Figure 8. This analysis considers the emission contributions of both main materials, namely concrete and reinforcing steel, thus providing a comprehensive picture of the carbon footprint of each configuration. In contrast to the beam analysis results, some additional column concrete strength results reveal interesting observations. For both section sizes, columns made with weaker concrete had more embodied carbon. This is counterintuitive because weaker concrete is typically associated with lower emissions. However, the opposite is true when considering the structural performance of the column. When concrete with a limited compressive strength is used, the amount of reinforcing steel required for the column is so large that it significantly increases the total embodied carbon. This is especially true for 25 and 28 MPa concrete, for which the concrete–steel ratio is such that the steel completely dominates the emissions of the system.

In addition, columns with smaller cross-sections (55 cm × 55 cm) consistently showed more embodied carbon than the larger cross-sections (60 cm × 60 cm). While smaller cross-sections used less concrete, they required appreciably more steel reinforcement to meet the strength requirement of the benchmark. As shown in the earlier reinforcement ratio analysis (Figure 7), there was a rapid increase in the steel content with a decrease in the section size. Because steel has a much greater carbon intensity than concrete, an increase in steel content has a disproportionate effect on the total embodied carbon.

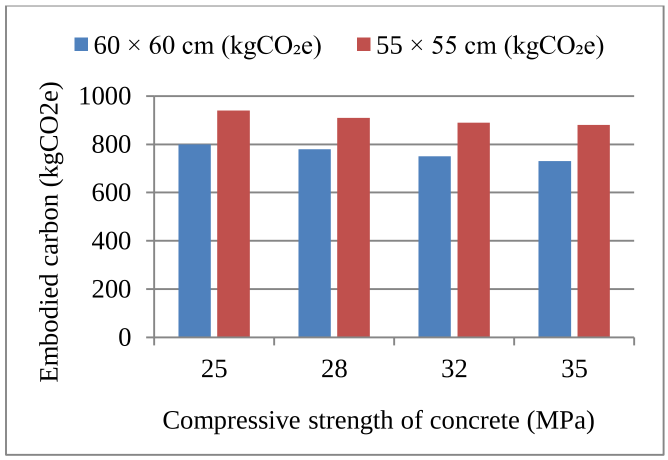

Fig. 8 Total embodied carbon of RC column for different concrete grades

This is completely opposite to the results for the RC beams. For RC beams, the volume of concrete is the major factor determining the level of embodied carbon. In columns, the predominant material responsible for the carbon footprint is reinforcement steel, especially when there is a high reinforcement ratio owing to design constraints, low concrete strength, or both.

Figure 9 shows the total material cost of each configuration for the reinforced concrete columns, which was made up of the cost of concrete and reinforcement. The resulting trends are almost identical to those from the embodied carbon analysis, once again confirming the relationship between economic and environmental considerations for material-intensive structural components, such as columns.

The findings indicate that columns with lower concrete compressive strengths have higher total construction costs. This is mainly because of the higher reinforcement requirements required to achieve the same structural strength. As shown previously in the reinforcement ratio analysis (Figure 7), lower-strength concrete necessitates the use of more steel, and considering the higher cost of reinforcing steel compared to concrete, the costs increase. For example, the 55 × 55 cm column with 25 MPa concrete exhibited the highest total material cost. This was mainly owing to the quantities of concrete and reinforcing steel.

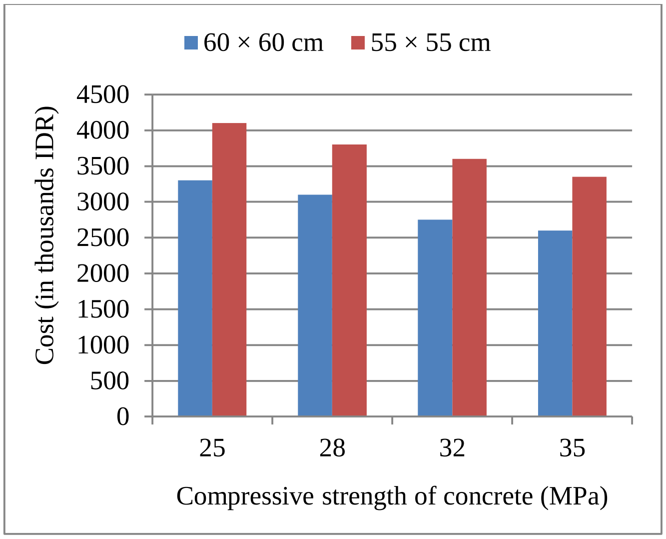

Fig. 9 Total cost of RC column for different concrete grades

In addition, the smaller section columns (55 × 55 cm) resulted in higher costs compared to the larger columns (60 × 60 cm) at all levels of concrete strength, and this was true for all levels of concrete strength. Smaller columns have lower concrete volumes, but they require much more reinforcement than larger columns to achieve the same design performance. Thus, there are no cost savings from a smaller size. The cost penalty due to reinforcement is sufficient to account for the higher total cost of smaller sections.

The most inexpensive option is the 60 × 60 cm column made with 35 MPa concrete, owing to the minimum 1% requirement for reinforcement and the minimal steel content. This reinforces the conclusion that primary carbon and construction cost savings on columns are attainable with high-strength concrete.

The findings reiterate the need to balance structural efficiency with cost and sustainability when designing columns. Designers should not reduce the cross-sectional area or use lower-strength concrete under the misconception that costs will be reduced. The increased costs related to the higher reinforcement must be factored in, and, in most instances, the rule of thumb holds that higher-strength concrete will be more cost- and carbon-efficient overall.

3.3. Sensitivity Analysis of Concrete Emission Factor

To evaluate the robustness of the results on embodied carbon, a sensitivity analysis was performed, focusing on the variations in the emission factor of concrete. The embodied carbon of concrete depends greatly on its mix design parameters, such as cement content, use of supplementary cementitious materials, and sourcing of raw materials. Even for concrete mixtures with the same nominal compressive strength, parameters within the range of a single supplier and across suppliers can differ significantly. However, there is more stability with the emission factor of reinforcing steel as a standardised production method and steelmaking technology. Therefore, a deterministic sensitivity analysis was performed, wherein only the emission factor for concrete was varied. For this analysis, other factors, including the quantities of steel reinforcements and emission factors of steel, were held constant, while the emission factor varied within a range of ±10% of the baseline value. This approach enables a more definitive analysis of the uncertainty of the composition of the concrete mix and its impact on the total embodied carbon, which serves to validate the integrity of design comparisons and the conclusions drawn based on them.

Tables 3 and 4 summarise the results of the sensitivity analysis, noting that the total embodied carbon shows moderate impacts when examining the emission factor of concrete for all beam and column configurations. For reinforced concrete beams, the total embodied carbon changes by approximately ±6% to ±9% for ±10% changes in the concrete carbon factor. The sensitivity was greatest for larger beam sections, especially for those with dimensions of 100 × 30 cm. This is reasonable because deeper beams use more concrete; therefore, more embodied carbon is likely to be affected by the carbon emission factors. The smaller 60 × 30 cm sections still demonstrate the dominant role of concrete in the embodied emissions of flexural members, as evidenced by the sensitivity remaining in the ±6 to 7% range.

For each column type, the variance with respect to concrete carbon was between ±4% and ±8%. This variance also depends on the column size and concrete grade. In most cases, the larger column sections of 60 × 60 cm tended to be slightly more sensitive than the 55 × 55 cm sections. This is because more concrete is provided. However, compared to the beams, the overall magnitude of sensitivity was lower. This is because concrete reinforcement was more significant with steel, particularly in configurations with less concrete, smaller dimensions, or lower concrete grades, where the reinforcement ratio was more significant.

These trends hold in the primary analysis and design options with respect to order of magnitude, including the market benefits of high-strength concrete used in column construction. In addition, the relative carbon efficiency of the smaller concrete beams (or lighter concrete beams) did not change. This suggests that the variability in concrete mix design is practical for early-stage structural design and sustainability evaluation of the remaining margin. This supports the practicality of this study for early-stage structural design and sustainability evaluation.

Table 3. Sensitivity analysis results for reinforced concrete beams under ±10% variation in the concrete embodied carbon factor

Beam section	Fc'	Total embodied carbon ($kgCO_2e$)			Sensitivity	
		Δ -10%	Δ 0%	Δ 10%	Δ -10%	Δ 10%
60 x 30 cm	25	463	493	523	-6%	6%
	28	478	512	543	-7%	6%
	32	495	530	566	-7%	7%
	35	520	557	595	-7%	7%
80 x 30 cm	25	493	533	574	-8%	8%
	28	513	558	600	-8%	7%
	32	552	600	647	-8%	8%
	35	585	636	686	-8%	8%
100 x 30 cm	25	555	605	656	-8%	8%
	28	580	636	688	-9%	8%
	32	629	688	748	-9%	9%
	35	670	733	796	-9%	9%

Table 4. Sensitivity analysis results for reinforced concrete column under ±10% variation in concrete embodied carbon factor

Column section	Fc'	Total embodied carbon ($kgCO_2e$)			Sensitivity	
		Δ -10%	Δ 0%	Δ 10%	Δ -10%	Δ 10%
60 x 60 cm	25	771	811	851	-5%	5%
	28	741	785	827	-6%	5%
	32	704	752	799	-6%	6%
	35	687	737	799	-7%	8%
55 x 55 cm	25	913	947	981	-4%	4%
	28	879	917	952	-4%	4%
	32	862	902	942	-4%	4%
	35	839	882	924	-5%	5%

3.4. Design Implications

These findings highlight how variations in concrete compressive strength affect the environmental and economic impacts of Reinforced Concrete (RC) beams and columns, even when the structural capacity of all configurations remains constant. This provides important considerations for structural design that emphasise resource efficiency and sustainability with respect to sectional geometry and embodied carbon intensity.

Regarding RC beams, when the reinforcement is designed to achieve a constant nominal moment strength, increasing the concrete compressive strength has a limited influence on the flexural capacity. However, higher-strength concrete increases the embodied carbon and construction costs owing to the greater cement content, higher unit prices, and only marginal reductions in reinforcement demand. This effect is more pronounced in larger beam sections (e.g., 100 cm × 30 cm), where the concrete volume dominates the total carbon emissions. Smaller beam sections (e.g., 60 cm × 30 cm) demonstrated lower embodied carbon and cost despite higher reinforcement ratios. The sensitivity analysis further supports the robustness of this trend in the results. Therefore, low-to-moderate concrete grades (25-28 MPa), combined with efficient section sizing, provide improved material efficiency for flexure-dominated structures.

Reinforced concrete columns exhibited different patterns. For equivalent axial-flexural capacity, lower-strength concrete requires a much higher reinforcement ratio, especially at small cross-sections (e.g., 55 cm × 55 cm). Because steel has a higher carbon intensity and cost per unit mass than concrete, this increase in reinforcement results in a higher total carbon and cost. Conversely, larger cross-sections (e.g., 60 × 60 cm) combined with higher-strength concrete (32-35 MPa) reduce the need for reinforcement and improve environmental and economic performances. Sensitivity analysis confirmed that the embodied carbon of the columns was more influenced by the reinforcement content than by the variability in the concrete emission factor.

These differences in the results indicate that design optimisation requires a specific element-by-element analysis. Beams benefit more from low-strength concrete with efficient cross-sections, whereas columns are better suited to high-strength concrete with proportional cross-sections. Therefore, sustainable structural design requires strategies tailored to the mechanical roles of each element.

It should be emphasised that the guidelines in this study were derived from element-level analyses under controlled loading conditions. In complex structural systems, such as multi-story or irregular buildings, factors such as load redistribution, element interactions, serviceability requirements, and architectural constraints can influence optimal material choices. Therefore, these findings should be understood as fundamental design principles rather than rigid rules applicable to the entire system. For practical purposes, the integration of element-level material efficiency with a comprehensive system-level analysis is highly recommended.

Based on the findings of this study, the following guidelines are proposed to support more sustainable reinforced concrete design practices.

- For reinforced concrete beams (flexural-dominated elements): Prioritise the use of low- to medium-strength concrete (25-28 MPa). Among these elements, increasing concrete quality makes a limited contribution to flexural capacity but has a significant impact on increasing carbon emissions and construction costs.
- For reinforced concrete columns (compression-dominated elements), select higher-strength concrete (32-35 MPa). This approach effectively reduces the need for steel reinforcement, which, in turn, minimises the total embodied carbon emissions and construction costs.
- For beams, smaller sections have the potential to result in a lower carbon footprint and cost, provided they are designed efficiently. However, the verification of serviceability criteria, particularly deflection and vibration, is essential.
- For columns, the combination of a larger cross-sectional area with high-strength concrete (32-35 MPa) has been shown to provide more sustainable and economical results than smaller sections with solid reinforcement.
- Avoid excessive material specifications once the structural capacity target has been reached. A simultaneous optimisation approach for cross-sectional dimensions and material quality has proven to be more effective than optimising either parameter separately.
- Different design approaches are applied to beams and columns. Material selection decisions should align with the structural role of each element and holistically consider its life cycle impacts.

This synthesis of findings offers performance-based guidance that enables engineers to balance structural adequacy, carbon emissions, and cost efficiency in an integrated way. Importantly, applying this guidance to complex projects requires a comprehensive system-level evaluation to ensure holistic design optimisation.

4. Conclusion

This study investigates the effect of concrete compressive strength (25, 28, 32, and 35 MPa) on the carbon emissions and material costs of reinforced concrete beams and columns, based on equivalent structural performance. Element design follows a code-based procedure: beams are designed with a constant nominal flexural capacity, whereas columns are adjusted in their reinforcement ratios to achieve the same axial-moment interaction strength. Carbon emissions and costs were evaluated from the cradle-to-gate stage, encompassing both concrete and reinforcing steel, and were complemented by a deterministic sensitivity analysis of the concrete emission factor.

In RC beams, increasing concrete quality has little impact on flexural capacity but causes an increase in carbon emissions and costs owing to higher cement content and a negligible reduction in reinforcement. Smaller beam sections, despite requiring larger reinforcement ratios, result in lower total carbon emissions and costs. This confirms that the concrete volume is the dominant factor in the beam material efficiency. Therefore, the use of low- to medium-strength concrete (25-28 MPa) combined with efficient sections is recommended to optimise the environmental and economic performance of beam design.

In contrast to beams, increasing the concrete quality in RC columns significantly reduces the amount of reinforcement required to achieve an equivalent axial-flexural capacity. Although high-strength concrete has a higher emission factor, the substantial reduction in reinforcement, given the significantly higher carbon intensity and cost of steel, results in lower total carbon emissions and costs. Thus, compression-dominated elements, such as columns, benefit more from the use of higher-strength concrete (32-35 MPa) and proportionally sized cross-sections.

It should be noted that the analysis in this study was conducted in a deterministic framework with fixed input parameters, which allowed for the controlled isolation of the influence of concrete quality as the primary variable. Although a sensitivity analysis was performed on the concrete emission factors, probabilistic uncertainty and stochastic modelling were not included in the study.

Furthermore, unlike algorithm-based multi-objective optimisation studies, this study did not aim to find a global optimal solution; instead, it used a performance-based parametric comparison to understand the material efficiency mechanisms at the element level. Future research should integrate probabilistic modelling or optimisation techniques to broaden the scope and explore broader design considerations.

This study utilised data on material unit prices and embodied carbon factors from the Indonesian context. The implication is that while qualitative findings regarding material efficiency mechanisms may be generalisable, quantitative values such as absolute costs or emissions cannot be directly transferred to other regions without considering differences in local economic and environmental factors. Nevertheless, the contrasting trends identified between flexure-dominated and compression-dominated members are rooted in structural mechanics principles and are therefore expected to remain qualitatively transferable to future studies. As the findings were derived from analytical modelling rather than experimental validation, further cross-regional studies and experimental investigations are recommended to confirm and generalise the conclusion.

Acknowledgements

The authors appreciate the support provided by the Karbonara Research Institute for every aspect and resource allocated in this research. The authors are also thankful to the Civil Engineering Department of BINUS University for their endless support and guidance, and for providing the authors with the research instruments and equipment.

Funding Statement

This work was supported by Bina Nusantara University.

Author Contribution

RS prepared the manuscript, MK performed the analysis, MS reviewed the manuscript, and MA reviewed the manuscript.

Data availability

Data analysis https://zenodo.org/records/15455567

References

[1] 2022 Global Status Report for Buildings and Construction, UNEP, 2022. [Online]. Available: https://www.unep.org/resources/publication/2022-global-status-report-buildings-and-construction

[2] 2021 Global Status Report for Buildings and Construction, UNEP, 2021. [Online]. Available: https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction

[3] Z. Cao et al., "Deep Decarbonization Pathways for the Cement and Concrete Cycle in the United States, India, and China," *Industrial Sustainability Analysis Laboratory, Northwestern University*, 2021. [Google Scholar]

[4] Paulo J.M. Monteiro, Sabbie A. Miller, and Arpad Horvath, "Towards Sustainable Concrete," *Nature Materials*, vol. 16, no. 7, pp. 698-699, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[5] G.P. Hammond, and C.I. Jones, "Embodied Energy and Carbon in Construction Materials," *Proceedings of Institution of Civil Engineers: Energy*, vol. 161, no. 2, pp. 87-98, 2008. [CrossRef] [Google Scholar] [Publisher Link]

[6] Whole Life Carbon Assessment for the Built Environment, 2nd ed., Royal Institution of Chartered Surveyors (RICS), London, 2024. [Online]. Available: https://www.rics.org/profession-standards/rics-standards-and-guidance/sector-standards/construction-standards/whole-life-carbon-assessment

[7] Orlando Gibbon, Arup John Orr, and W. Arnold, "How to Calculate Embodied Carbon," *The Institution of Structural Engineers*, 2020. [Google Scholar]

[8] BS 15978: 2011, Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method, 2011. [Google Scholar] [Publisher Link]

[9] Dezhi Li et al., "A Methodology for Estimating the Life-Cycle Carbon Efficiency of a Residential Building," *Building and Environment*, vol. 59, pp. 448-455, 2013. [CrossRef] [Google Scholar] [Publisher Link]

[10] Andrea Meneghelli, "Whole-Building Embodied Carbon of a North American LEED-Certified Library: Sensitivity Analysis of the Environmental Impact of Buildings Materials," *Building and Environment*, vol. 134, pp. 230-241, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[11] Alice M. Moncaster et al., "Why Method Matters: Temporal, Spatial and Physical Variations in LCA and their Impact on Choice of Structural System," *Energy and Buildings*, vol. 173, pp. 389-398, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[12] Zahra S. Moussavi Nadoushani, and Ali Akbarnezhad, "Effects of Structural System on the Life Cycle Carbon Footprint of Buildings," *Energy and Buildings*, vol. 102, pp. 337-346, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[13] J. Monahan, and J.C. Powell, "An Embodied Carbon and Energy Analysis of Modern Methods of Construction in Housing: A Case Study using a Lifecycle Assessment Framework," *Energy and Buildings*, vol. 43, no. 1, pp. 179-188, 2011. [CrossRef] [Google Scholar] [Publisher Link]

[14] Geoff Hammond, and Craig Jones, "Inventory of Carbon and Energy (ICE) Data Base V3.0," *Retrieved November* 10, 2019. [Google Scholar]

[15] Ali Kaveh, R.A. Izadifard, and L. Mottaghi, "Optimal Design of Planar RC Frames Considering CO_2 Emissions using ECBO, EVPS and PSO Metaheuristic Algorithms," *Journal of Building Engineering*, vol. 28, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[16] S. Eleftheriadis et al., "Investigating Relationships Between Cost and CO_2 Emissions in Reinforced Concrete Structures using a BIM-based Design Optimisation Approach," *Energy and Buildings*, vol. 166, pp. 330-346, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[17] Roland Bechmann, and Stefanie Weidner, "Reducing the Carbon Emissions of High-Rise Structures from the Very Beginning," *CTBUH Journal*, no. 4, pp. 30-35, 2021. [Google Scholar]

[18] C.H. Goodchild, R.M. Webster, and K.S. Elliott, "Economic Concrete Frame Elements to Eurocode 2," *The Concrete Centre*, Camberley, Surrey, UK, 2009. [Google Scholar]

[19] Hoang Tran Mai Kim Trinh, Sanaul Chowdhury, and Tingting Liu, "Assessing Embodied Carbon of Flat Slab Buildings-an ANN-Integrated Optimization Methodology," *Journal of Cleaner Production*, vol. 457, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[20] SNI 2847-2019 Structural Concrete Requirements for Buildings SNI 1726-2019 Structural Concrete Requirements for Buildings, Gadjah Mada University, 2019. [Online]. Available: https://tekonsipil.sv.ugm.ac.id/file/sni-2847-2019-persyaratan-beton-struktural-untuk-bangunan-gedung-sni-1726-2019-persyaratan-beton-struktural-untuk-bangunan-gedung/

[21] ACI CODE-318-19(22): Building Code Requirements for Structural Concrete and Commentary, ACI, 2022. [Online]. Available: https://www.concrete.org/store/productdetail.aspx?ItemID=318U19&Language=English&Units=US_Units

[22] John Orr, Orlando Gibbons, and Will Arnold, *A Brief Guide to Calculating Embodied Carbon*, Apollo - University of Cambridge Repository, pp. 22-27, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[23] LETI 2024 Embodied Carbon Primer, LETI, 2024. [Online]. Available: https://www.leti.uk/ecp

[24] Michael Samson, and Roger Pope, "A Comparative Embodied Carbon Assessment of Commercial Buildings," *Structural Engineers*, vol. 90, no. 10, pp. 38-49, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[25] Thong Jia Wen, Ho Chin Siong, and Z.Z. Noor, "Assessment of Embodied Energy and Global Warming Potential of Building Construction using Life Cycle Analysis Approach: Case Studies of Residential Buildings in Iskandar Malaysia," *Energy and Buildings*, vol. 93, pp. 295-302, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[26] Vincent J.L. Gan et al., "A Comparative Analysis of Embodied Carbon in High-Rise Buildings Regarding Different Design Parameters," *Journal of Cleaner Production*, vol. 161, pp. 663-675, 2017. [CrossRef] [Google Scholar] [Publisher Link]