City Research Online

City St George's, University of London

Citation: Mergos, P. E. (2024). Structural design of reinforced concrete frames for minimum amount of concrete or embodied carbon. Energy and Buildings, 318, 114505. doi: 10.1016/j.enbuild.2024.114505

This is the accepted version of the paper.

This version of the publication may differ from the final published version. To cite this item please consult the publisher's version.

Permanent repository link: https://openaccess.city.ac.uk/id/eprint/33285/

Link to published version: https://doi.org/10.1016/j.enbuild.2024.114505

Copyright and Reuse: Copyright and Moral Rights remain with the author(s) and/or copyright holders. Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge, unless otherwise indicated, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way. For full details of reuse please refer to City Research Online policy.

City Research Online: http://openaccess.city.ac.uk/ publications@citystgeorges.ac.uk

Structural design of reinforced concrete frames for minimum amount of concrete or embodied carbon

Panagiotis E. Mergos [a,*]

[a] *Department of Engineering, City, University of London, London EC1V 0HB, UK*

Abstract.

In standard engineering practice, designers often aim to minimize the amount and volume of concrete in reinforced concrete (RC) frames by reducing the size of member cross-sections. This is done either for architectural reasons or because it is assumed to drive to more economic and environmentally friendly productions. The present study, for first time, compares the environmental footprint of RC frames designed for minimum concrete volume against designs for minimum embodied carbon. To serve this goal, six realistic 3D RC building frames are optimally designed for parametric values of the carbon factors of concrete and reinforcing steel materials. In this comparison, it is noticed that the carbon factors ratio R of reinforcing steel to concrete plays a key role. More particularly, it is found that for $R \leq 10$ the designs for minimum concrete and carbon practically coincide. This is a useful observation since it signals a clear direction to designers to decrease concrete sections to achieve minimum environmental impact. Nevertheless, as R increases from 10, the two designs gradually deviate since the carbon footprint of rebars becomes more important. For high R values, the RC frames with the least amount of concrete may produce, on average, up to 40% more embodied carbon than the most environmentally clean designs.

Keywords: Reinforced concrete; Frames; Embodied Carbon; Structural Optimization; Environmentally friendly

Acknowledgments and Funding Information

No funding was received to assist with the preparation of this manuscript.

1 Introduction

Climate change imposes significant threats to people and ecosystems [1]. Anthropogenic greenhouse gas emissions (GHG) are the main cause of current climate change [1]. The built environment is the main driver of anthropogenic GHG emissions contributing approximately 37% of global CO_2 [2]. Traditionally, emphasis is placed on reducing the operational carbon of the built environment. More recently, the embodied carbon of construction materials has

[*] Corresponding author. Panagiotis E. Mergos, Senior Lecturer in Structural Engineering, Research Centre for Civil Engineering Structures, City, University of London, London, EC1V 0HB, UK.
E-mail address: panagiotis.mergos.1@city.ac.uk, Tel. 0044 (0) 207040 8417

come under the spotlight of structural engineering research and professional communities [3]. The latter carbon originates from the production, construction, use and end of life cycle stages of construction materials.

Reinforced concrete (RC) structures are ubiquitous in the built environment. Their embodied environmental impact is the sum of the contributions of concrete and reinforcing steel materials. The environmental footprint of concrete originates mainly from cement. Cement alone is responsible for approximately 7% of global CO_2e [2]. It is reported [3-5], that the environmental impact of concrete, for a given strength, can vary up to 3 times depending on the amount of Portland cement. Portland cement can be partially replaced by alternative cementitious products, known as Supplementary Cementing Materials (SCMs), such as Pulverised Fly Ash (PFA), Ground Granulated Blast Furnace Slag (GGBS) and limestone. Cement replacement reduces drastically the embodied carbon of concrete. In the UK, for example, the expected carbon of C25/30 concrete drops from e_c = 0.12kgCO_2e/kg for no cement replacement to e_c = 0.06kgCO_2e/kg for 70% cement replacement by GGBS [3-4].

The carbon footprint of rebars is mainly related to the energy required to process and reform steel scrap and iron ore. On average globally, it is estimated that 1kg of steel reinforcement generates roughly a concerning impact of 2kgCO_2e [3-4]. However, the latter amount may vary significantly (i.e. between 0.4kgCO_2e and 4kgCO_2e [3-4]) depending on the scrap content and steel production route: Basic Oxygen Furnace (BOF) or Electric Arc Furnace (EAF) [3-4]. BOF, also called Blast Furnace (BF), is powered by fossil fuels and permits only small scrap contents (i.e. up to 30% scrap). On the other hand, EAF uses electricity and allows for very high recycled steel contents (i.e. up to 100%). Rebars produced by EAF with high scrap content emit significantly lower embodied carbon than BOF with low recycled steel rates.

The previous observations highlight the urgent environmental need for efficient material design of RC structures [6-7]. Structural optimization represents the most formal approach to efficient material design [6-7]. Early studies to optimize the design of concrete structures concentrated on economic cost [8]. More recently, research efforts focussed on minimizing their environmental impact (e.g. [9-19]). Most of these studies conclude that the designs of RC structures for minimum cost and environmental impact are closely related and that the latter can reduce environmental footprint up to approximately 20% more than the former optimal designs. Yeo and Gabbai [11] correctly point out that the differences between minimum cost and minimum embodied environmental impact designs depend on the unit costs and unit environmental impacts of reinforcing steel and concrete materials. Furthermore, Medeiros and Kripka [13] show that the optimal designs of concrete columns may vary considerably when aiming to minimize different environmental impact indicators such as CO_2, global warming potential, eco-indicator and energy consumption. This is the case because concrete and rebars contribute differently to the various environmental impact indicators.

RC frames are perhaps the most common structural system in concrete structures. Nevertheless, the optimal design of RC frames is more challenging due to the complex and nonlinear interdependencies between structural members as well as the numerous design variables. Hence, the use of metaheuristic algorithms is generally recommended to tackle this optimization task [6,7]. Most existing optimization studies focus on planar RC frames (e.g. [9,10,12,14,17,20-24]). Still, there is a considerable amount of research efforts targeting 3D RC frames [7, 15, 19, 25-33]. From the latter studies, only [15] and [19] aim at minimizing environmental impact.

In carbon efficient structural design of RC structures, the focus is typically on using less concrete [34]. This is conveniently done by reducing concrete sections until designs become not feasible. The latter approach, that overlooks embodied carbon of rebars, stems from the assumption that the amount of concrete in RC frames is a proxy of their embodied carbon. This could be indeed the case if one of the following conditions is met: i) the embodied carbon of concrete is dominant when compared to the one of steel reinforcement; ii) the amount of steel reinforcement per cubic meter of concrete remains approximately constant in the efficient designs of RC structures. It is also recalled that less concrete drives to smaller structures in size that are typically linked to less embodied carbon.

The present study examines the validity of these assumptions and investigates, for first time, how environmentally friendly are concrete frames using the least amount of concrete when compared to frames designed for minimum environmental impact. This research question gains additional value when considering that the former designs can be appealing to architects/engineers/owners since minimizing the volume of concrete could lead to more elegant and aesthetically pleasing structures. Furthermore, smaller concrete structural members increase the useable space in buildings.

In the following, the methodology used in this study to optimally design RC frames for minimum concrete volume and/or embodied carbon is discussed. Then, six 3D RC building frames are designed optimally assuming parametric values for the unit environmental impacts of concrete and reinforcing steel materials. The optimal designs for minimum concrete volume and environmental impact are compared and useful conclusions are made.

2 Environmentally friendly design methodology

The ultimate goal of the environmentally friendly design methodology herein is to minimize the embodied environmental impact of RC frames. In this sense, it becomes a structural optimization problem. More specifically, the structural optimization problem herein seeks to select the cross-sections of concrete members that minimize the total environmental footprint of RC frames for a fixed set of design parameters $\boldsymbol{p}$ reflecting external loads, material mechanical properties, geometry, and boundary conditions (i.e. sizing optimization problem). To comply with standard construction practice, it is assumed that concrete members' cross-sections are taken from discrete lists of available cross-sections that are pre-specified by the designer. The afore-described, mixed-integer optimization problem is stated as follows:

$$
\begin{array}{lll}
\text{Minimize:} & E(\boldsymbol{x}) & \\
\text{Subject to:} & g_j(\boldsymbol{x}) \leq 0,\ j = 1\ to\ m & (1) \\
\text{Where:} & \boldsymbol{x} = (x_1, x_2, \dots, x_d) & \\
 & x_i \in \boldsymbol{D}_i = (1, 2, \dots, k_i)\ , i = 1\ to\ d &
\end{array}
$$

In Eq. (1), $E(\boldsymbol{x})$ is the environmental impact to be minimized for a given set of design parameters $\boldsymbol{p}$, and $\boldsymbol{x}$ is the design vector that consists of d independent variables x_i (i = 1 to d), representing the different cross-sections in the RC frame. More particularly, the design variables x_i take values from sets of integer values $\boldsymbol{D}_i = (1, 2, \ldots, k_i)$ and reflect the positions of cross-sections in the corresponding pre-allocated lists of cross-sections from the designer. In the latter lists, k_i is the total number of available cross-sections in the list for cross-section i (i = 1 to d). In addition to the above, the solution must be subject to m number of structural design constraints $g_j(\boldsymbol{x}) \leq 0$ (j = 1 to m) for the same set of design parameters $\boldsymbol{p}$.

The embodied environmental footprint $E(\boldsymbol{x})$ of RC frames is determined by Eq. (2), where V_c (m^3) and m_c (kg) stand for the total volume and mass of concrete in the frame respectively, ρ_c is concrete density (kg/m^3) and m_s (kg) represents the total mass of reinforcing steel accounting for both the longitudinal and transverse reinforcement in RC members. The environmental impact examined in this study is the embodied carbon of RC frames in terms of $kgCO_2e$. Hence in Eq. (2), e_c ($kgCO_2e/kg$) and e_s ($kgCO_2e/kg$) are the concrete and steel reinforcement carbon factors representing the corresponding materials' embodied carbon per unit mass.

$$E(\boldsymbol{x}) = m_c(\boldsymbol{x}) \cdot e_c + m_s(\boldsymbol{x}) \cdot e_s = V_c(\boldsymbol{x}) \cdot \rho_c \cdot e_c + m_s(\boldsymbol{x}) \cdot e_s \qquad (2)$$

It is noteworthy that, irrespectively of the values of carbon factors, all design solutions $\boldsymbol{x}$ minimizing Eq. (2) are Pareto-front solutions of the following bi-objective optimization problem aiming to minimize both the concrete volume $V_c(\boldsymbol{x})$ and the mass of steel reinforcement $m_s(\boldsymbol{x})$ of the RC frame.

$$
\begin{aligned}
&\text{Minimize:} && V_c(\boldsymbol{x}), m_s(\boldsymbol{x}) \\
&\text{Subject to:} && g_j(\boldsymbol{x}) \leq 0,\ j = 1\ to\ m \\
&\text{Where:} && \boldsymbol{x} = (x_1, x_2, \dots, x_d) \\
& && x_i \in \boldsymbol{D}_i = (1, 2, \dots, k_i)\ , i = 1\ to\ d
\end{aligned} \tag{3}
$$

For a fixed set of design parameters $\boldsymbol{p}$ and a given vector of design variables $\boldsymbol{x}$ (i.e. for known cross-sections of the RC frame), $V_c(\boldsymbol{x})$ is easily deducted by geometry and $m_s(\boldsymbol{x})$ can be determined by following standard structural analysis and design procedures. More specifically, herein, the RC frames are designed according to Eurocodes [35-37] with the aid of the well-known structural analysis and design software SAP2000 via its API [38]. First, the load cases and combinations are determined following the prescriptions of Eurocode 0 [36]. Then, structural analysis is conducted in SAP2000 [38] to calculate design action effects (i.e. bending moments, axial and shear forces). Next, concrete beams are designed in SAP2000 according to Eurocode 2 [35] for major bending and major shear to determine their longitudinal and transverse reinforcement, respectively. Furthermore, beams are designed for torsion to examine whether additional longitudinal and transverse reinforcement is required. For columns, the design bending moments are first enhanced to account for P-delta effects and imperfections. Then, the columns are designed, in SAP2000 following Eurocode 2, for biaxial bending and axial loading to determine their longitudinal reinforcement and against biaxial shear to establish their shear reinforcement. It is noted that, for simplicity, square column sections and rectangular sections are assumed herein with steel reinforcement configuration as shown in Fig. 1. Finally, the total mass $m_s(\boldsymbol{x})$ is calculated by summing up the masses of steel reinforcement of all beam and column members in the RC frame. More information and details regarding the methodologies and assumptions followed herein in the calculation of steel reinforcement of RC frames can be found in [32,39].

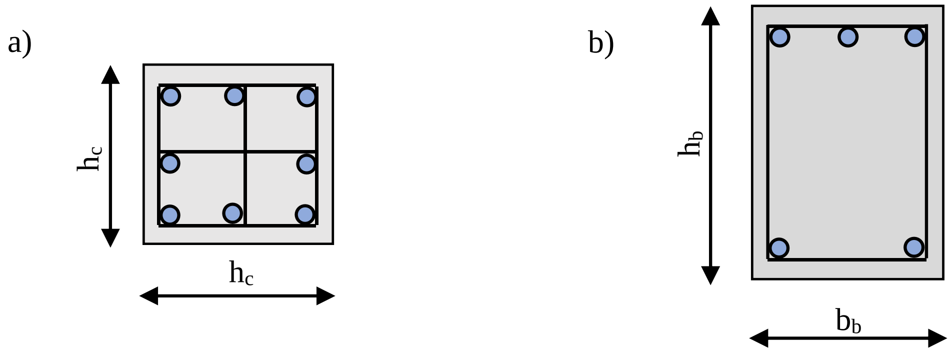

Fig. 1: Assumed concrete cross-sections and steel reinforcement configurations: a) columns; b) beams

The design constrains of the optimization framework presented herein regard the checks of Eurocode 2 [35] and Eurocode 8 [37] for ductility class Low (DCL) to meet ULS and SLS performance requirements. More specifically, due to the formulation of the optimization problem in Eq. (1), a design constraint concerning the flexural and shear design of the RC cross-sections at the ULS is considered not feasible when the corresponding design check cannot be fulfilled by any permissible amount of steel reinforcement in the section. This approach is adopted since only the frame cross-sections are treated as independent design variables in the optimization problem. Therefore, the flexural and shear design ULS constraints are written as shown in Eqs (4-5), where ρ_l and ρ_w are the required cross-section longitudinal and transverse steel reinforcement volumetric ratios respectively and $\rho_{l,max}$ and $\rho_{w,max}$ their corresponding maximum permissible values according to Eurocodes and construction practice.

$$\rho_l - \rho_{l,max} \leq 0 \tag{4}$$

$$\rho_w - \rho_{w,max} \leq 0 \tag{5}$$

Furthermore, to avoid diagonal compression failure due to the combined shear and torsional effects at the ULS according to Eurocode 2, the concrete sections must satisfy the following design constraints, where V_{Ed} and T_{Ed} are the shear force and torsional moment demands, respectively, and $V_{Rd,max}$ and $T_{Rd,max}$ are the corresponding diagonal compression capacities for an angle of compression struts $\theta = 45^o$.

$$\frac{V_{Ed}}{V_{Rd,max}} + \frac{T_{Ed}}{T_{Rd,max}} - 1 \leq 0 \tag{6}$$

In addition to ULS constraints, checks are required to confirm the fulfilment of SLS requirements. Typically, these are conducted in terms of displacements or deformations as presented in Eq. (7), where Δ represents displacements/deformations at the SLS and Δ_{max} their corresponding permissible values.

$$\Delta - \Delta_{max} \leq 0 \tag{7}$$

Especially in the case of RC beam deflections, it is conservatively assumed herein that EC2 SLS requirements are met when the actual beam span-to-depth ratio L/d remains below the corresponding permissible value [40], as shown in Eq. (8). This method guarantees that beam deflections do not exceed the span length divided by 250 [40].

$$\left(\frac{L}{d}\right) - \left(\frac{L}{d}\right)_{max} \leq 0 \tag{8}$$

3 RC frames

3.1 Description

Six different RC building frames B1-B6 are considered in this study, as shown in Fig. 2. The number of storeys of the RC frames ranges between two and six and the number of spans between one and three. All spans are of equal length ranging between 5m and 6m. Storey height is 3m. Concrete class is either C20/25 or C30/37 and the class of steel reinforcement is B500 following EC2 [35] specifications. Concrete cover to the centroid of the longitudinal steel reinforcement is 50mm.

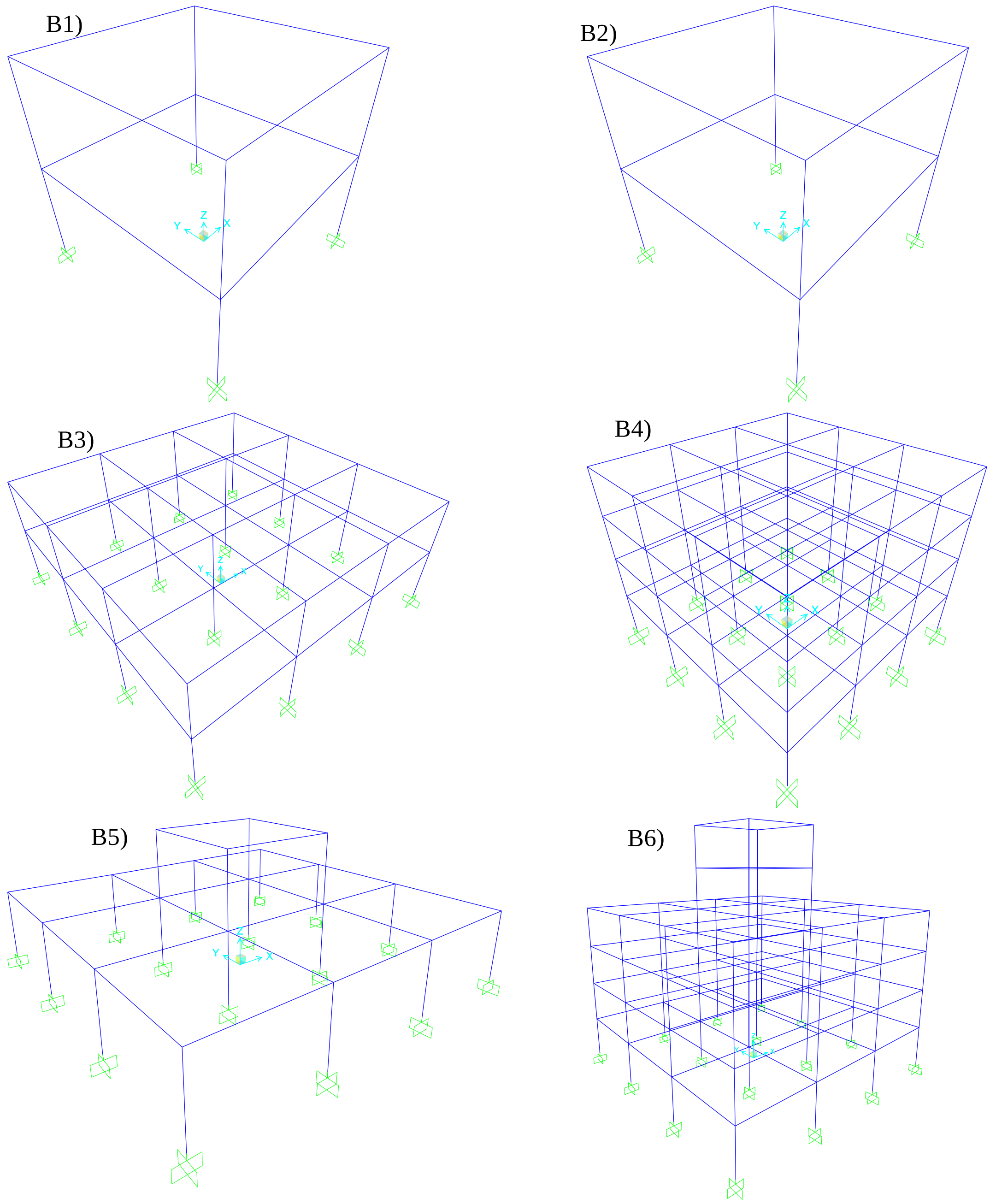

Fig. 2: RC frames structural configurations

The RC frames are subjected to dead, live and either wind or earthquake loads. The dead *g* and live *q* loads are applied to beams as uniformly distributed loads. Frames B1, B2 and B4 are designed for wind load. The wind pressure is assumed, for simplicity, to act uniformly along the vertical surfaces of the buildings in both horizontal directions. Frames B3, B5 and B6 are designed against earthquake loads. The earthquake loads are represented by the Type I response spectrum of Eurocode 8. All earthquake resistant frames are of importance class II and they are designed according to DCL in Eurocode 8 with behaviour factors q = 1.5. Furthermore, it is specified that inter-storey drifts should remain below 1% under frequent earthquakes to limit SLS damage. More details about the materials, geometry and loads of the concrete frames can be found in [41].

3.2 Candidate design solutions

In this section, the RC frames of §3.1 are designed according to the methodology described in §2 for various combinations of member cross-sections (i.e. candidate design solutions). More particularly, the optimization problem of Eq. (3) is addressed with an exhaustive search solution approach, where all possible design solutions $\boldsymbol{x}$ are examined to establish the ones offering the best trade-offs (i.e. Pareto-optimal) between $V_c(\boldsymbol{x})$ and $m_s(\boldsymbol{x})$, while satisfying all design constraints of Eqs (4-8). The solution procedure adopted is presented in Fig. 3. The exhaustive search solution algorithm is employed herein because it guarantees tracking of global optimal solutions and offers a valuable insight into the landscapes of the objective functions. On the negative side, it is typically accompanied by high computational costs.

To facilitate solution and for structural simplicity, the RC frames are divided into groups of concrete members of the same cross-sections. Following this approach, the number of design variables d (i.e. problem dimensions) coincides with the total number of member groups in the frames. Furthermore, the cross-sections of the member groups are taken from pre-determined lists of available cross-sections. These sections maintain the same structural configurations as shown in Fig. 1. A detailed description of the member groups and corresponding lists of cross-sections can be found in [41]. For all frames, d varies between 2 and 7. Based on the number of problem dimensions and the available lists of cross sections, the total number of candidate design solutions Ω (i.e. search space) can be deducted. For all six RC frames, Ω ranges between $\Omega = 10^2$ and $\Omega = 6^7$ candidate design solutions [41].

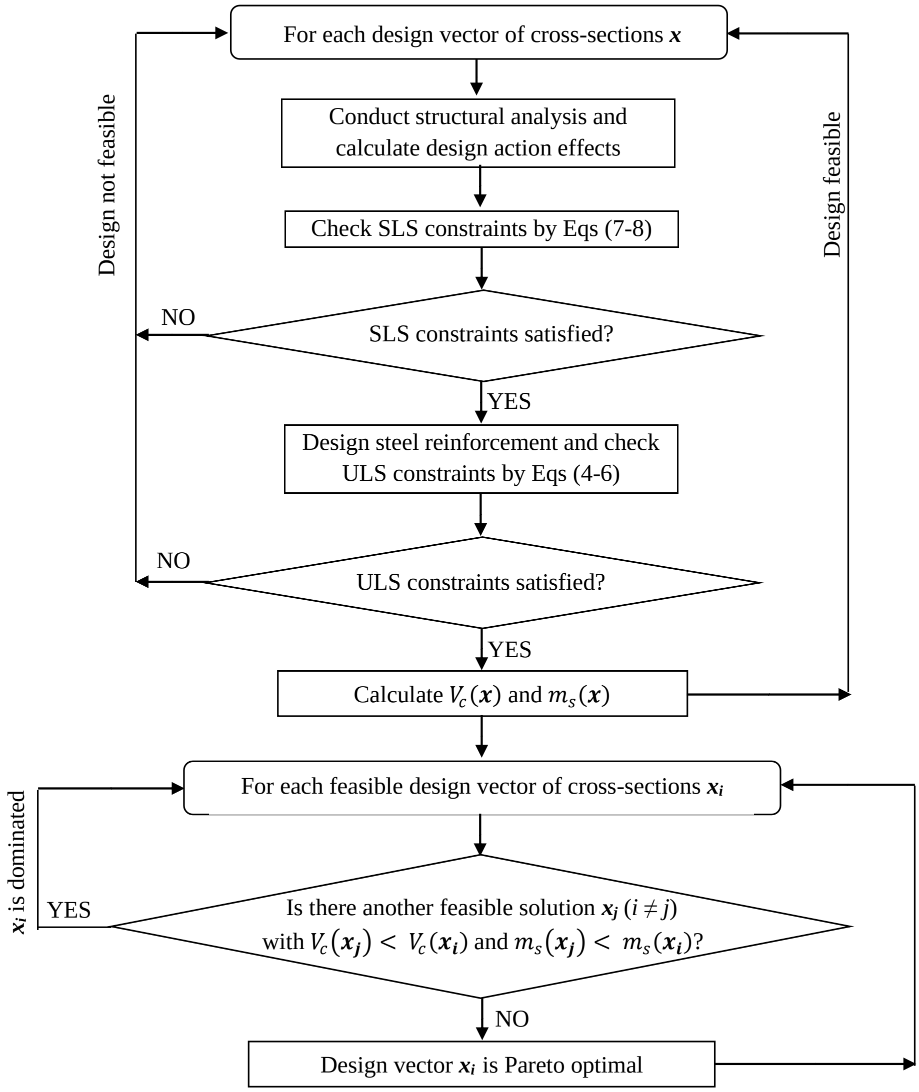

Fig. 3: Exhaustive search flowchart for solving the optimization problem of Eq. (3)

The relationships between $V_c(\boldsymbol{x})$ and $m_s(\boldsymbol{x})$ for all design solutions that satisfy design constraints is presented in Fig. 4. In Fig. 4, it can be inferred that as the concrete volume of the RC frames increases, typically, the mass of steel reinforcement decreases. However, there exist inefficient design solutions that require more reinforcement than others even with lesser concrete volumes. This is particularly seen in solutions of very large concrete volumes, where the minimum reinforcement requirements govern the designs. The results in Fig. 4 clearly indicate the need for structural designs that make the most efficient use of both concrete and reinforcing steel materials.

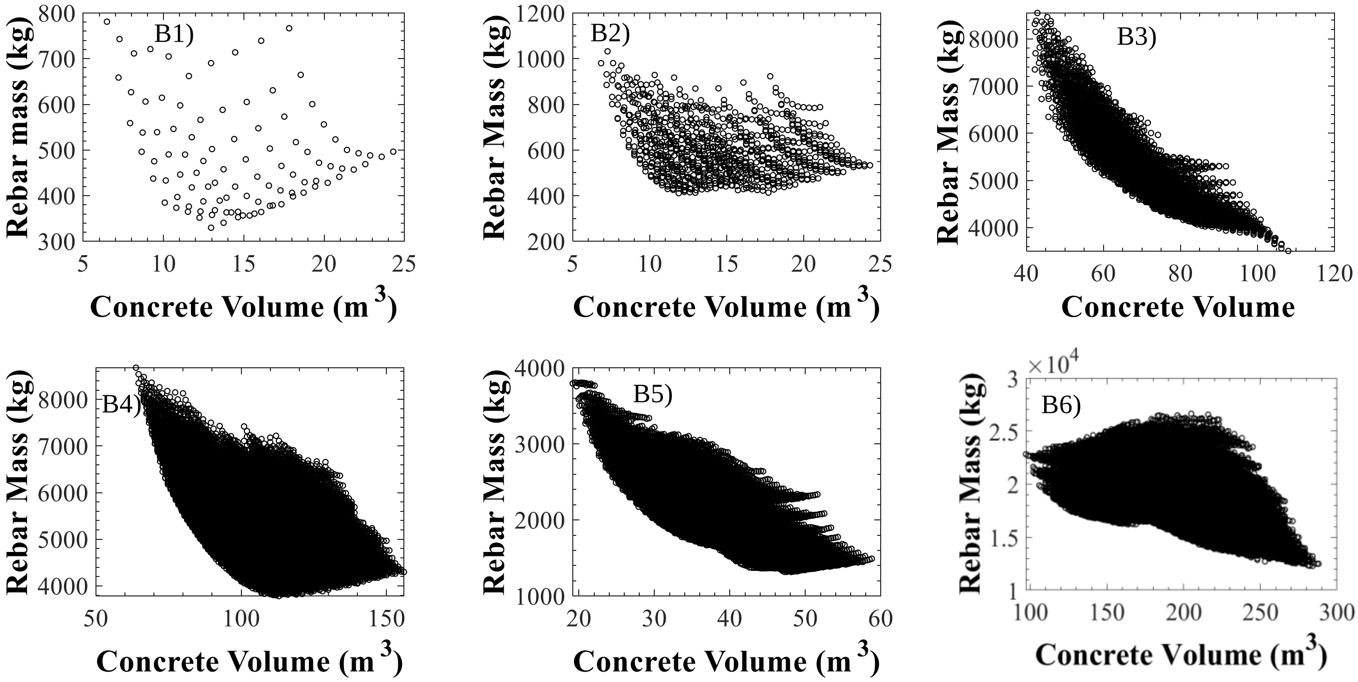

Fig. 4: $V_c(\boldsymbol{x})$ versus $m_s(\boldsymbol{x})$ relationships of all feasible design solutions

The designs that offer the best trade-offs between the two materials belong to the Pareto fronts of the $V_c(\boldsymbol{x})$ versus $m_s(\boldsymbol{x})$ relationships. These Pareto fronts are shown in Fig. 5. There exist no design alternatives that can reduce simultaneously both $V_c(\boldsymbol{x})$ and $m_s(\boldsymbol{x})$ with respect to these Pareto optimal solutions. The Pareto fronts show a clear conflicting relationship between reinforcement mass and concrete volume. It is also noteworthy that the tradeoffs between the two materials within the Pareto fronts are high. In most cases, $V_c(\boldsymbol{x})$ may increase within a Pareto front by 2 to 3 times leading to an equivalent 2 to 3 times reduction in $m_s(\boldsymbol{x})$.

Moreover, Fig. 6 demonstrates the relationships between the ratios of reinforcement mass to concrete volume $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ versus $V_c(\boldsymbol{x})$ of the Pareto optimal solutions. $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ ratios are widely used in industry to quantify the density of steel reinforcement within concrete structures. As expected, there are strong conflicting relationships between $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ versus $V_c(\boldsymbol{x})$. Despite the fact that the ratios $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ are normalized parameters, it is seen that they range between different values among the Pareto fronts of the various RC frames. Hence, it is concluded that these ranges are rather problem specific.

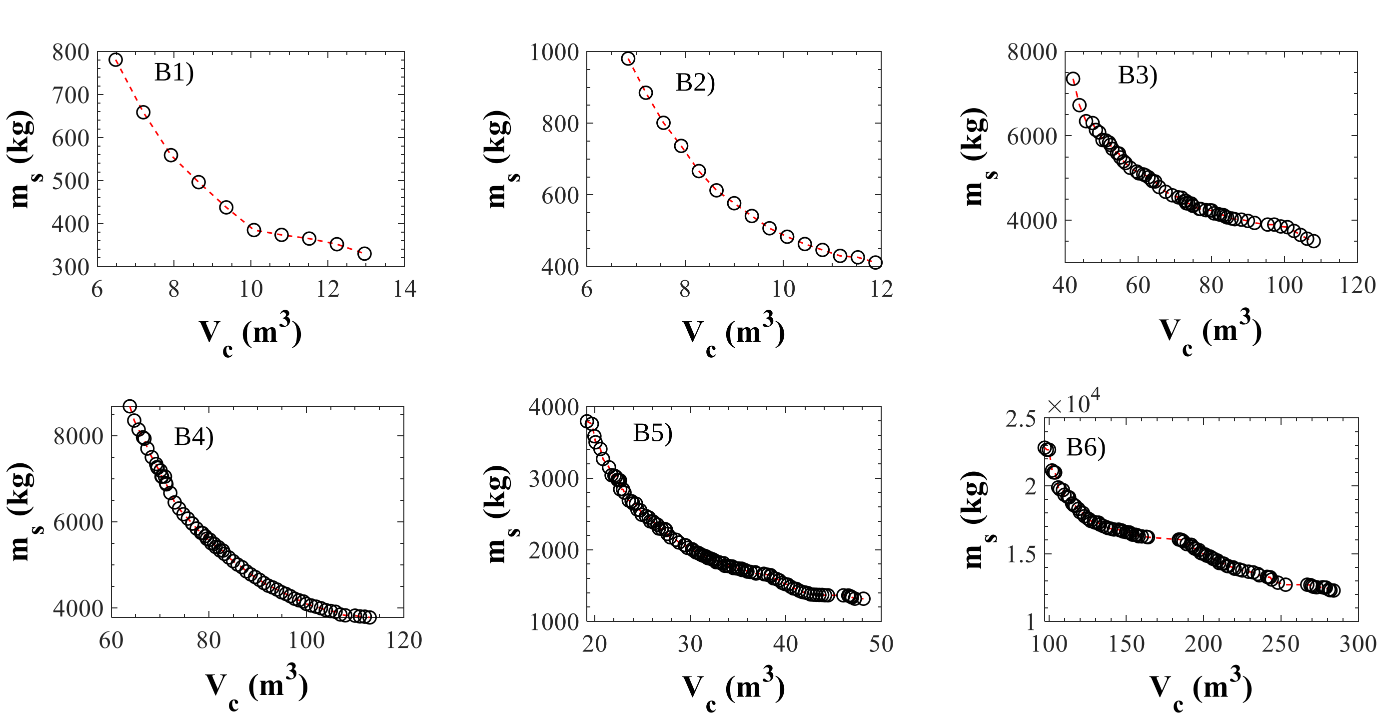

Fig. 5: $V_c(\boldsymbol{x})$ versus $m_s(\boldsymbol{x})$ Pareto optimal solutions

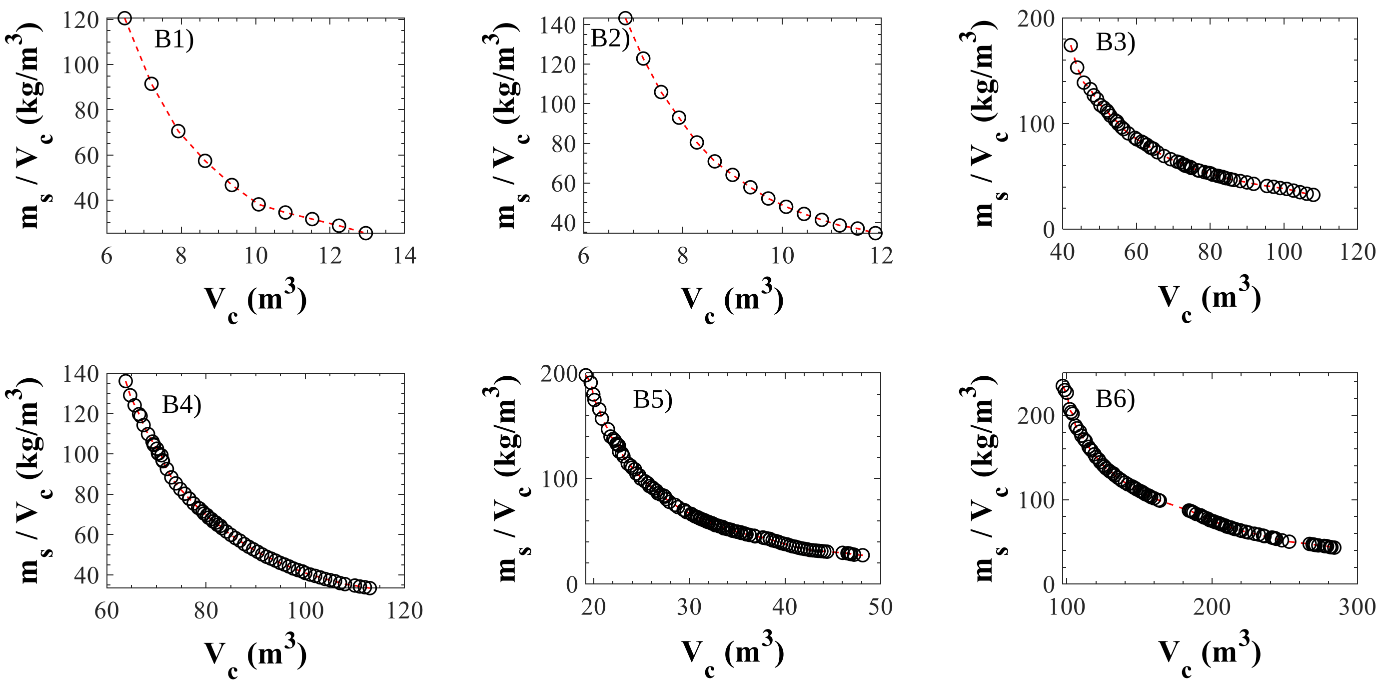

Fig. 6: $V_c(\boldsymbol{x})$ versus $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ of Pareto optimal solutions

4 Environmentally friendly designs

4.1 Optimal designs for fixed carbon factors

The main objective of this section is to investigate the properties of the most environmentally friendly design solutions of the RC frames, that minimize the objective function of Eq. (2), for given carbon factors values. As discussed, all design solutions minimizing $E(\boldsymbol{x})$ belong to the Pareto fronts of Fig. 5. The most environmentally friendly Pareto optimal solution depends on the values of the material carbon factors e_c and e_s. Two separate scenarios regarding the values of these carbon factors are examined in the rest of this section.

In the first scenario, the carbon factors e_c and e_s assume the 'typical' values recommended for the UK in [3]. These are: e_c = 0.093kgCO_2e/kg for C20/25; e_c = 0.1kgCO_2e/kg for C25/30; e_c = 0.114kgCO_2e/kg for C30/37 and e_s = 0.76kgCO_2e/kg. Fig. 7 presents the variation of concrete, reinforcing steel and total embodied carbon of the RC frames against the volume of concrete of the Pareto optimal solutions. Interestingly, in all RC frames, the minimum carbon design approximately coincides with the minimum concrete volume design. This is an interesting and quite useful observation since it means that, under this scenario, if designers minimize the volume of concrete in RC frames, then they simultaneously minimize environmental impact. Fig. 8 shows the variation of the embodied carbon of the RC frames versus the $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ ratios of the Pareto optimal solutions. It is seen that the most environmentally friendly solutions always approximately match the solutions with the maximum density of steel reinforcement in concrete. Nevertheless, the maximum $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ ratios vary across the various RC frames. This again shows that the optimal $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ ratios are rather problem specific. The latter contradicts a common misconception in engineering practice assuming that all RC frames maintain similar optimal $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ ratios.

In the second scenario examined herein, greener concrete materials are assumed with 70% cement replacement by GGBS and carbon factor values e_c = 0.053kgCO_2e/kg for C20/25; e_c = 0.056kgCO_2e/kg for C25/30 and e_c = 0.06kgCO_2e/kg for C30/37 according to [3]. Furthermore, a worldwide average value of e_s = 1.96kgCO2e/kg is considered for steel reinforcement, as recommended in [3]. Figs 9 and 10 present the variation of embodied carbon against $V_c(\boldsymbol{x})$ and $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ of the Pareto optimal solutions under the second carbon factors scenario. Different conclusions are drawn in the new scenario. It is seen that the minimum $V_c(\boldsymbol{x})$ solutions are not the most environmentally friendly anymore. On the contrary, the solutions with minimum embodied carbon may use significantly more concrete than the minimum possible. Similarly, the optimal $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ ratios may be significantly smaller than their maximum Pareto values. Again, it is observed that the optimal $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ ratios are problem specific.

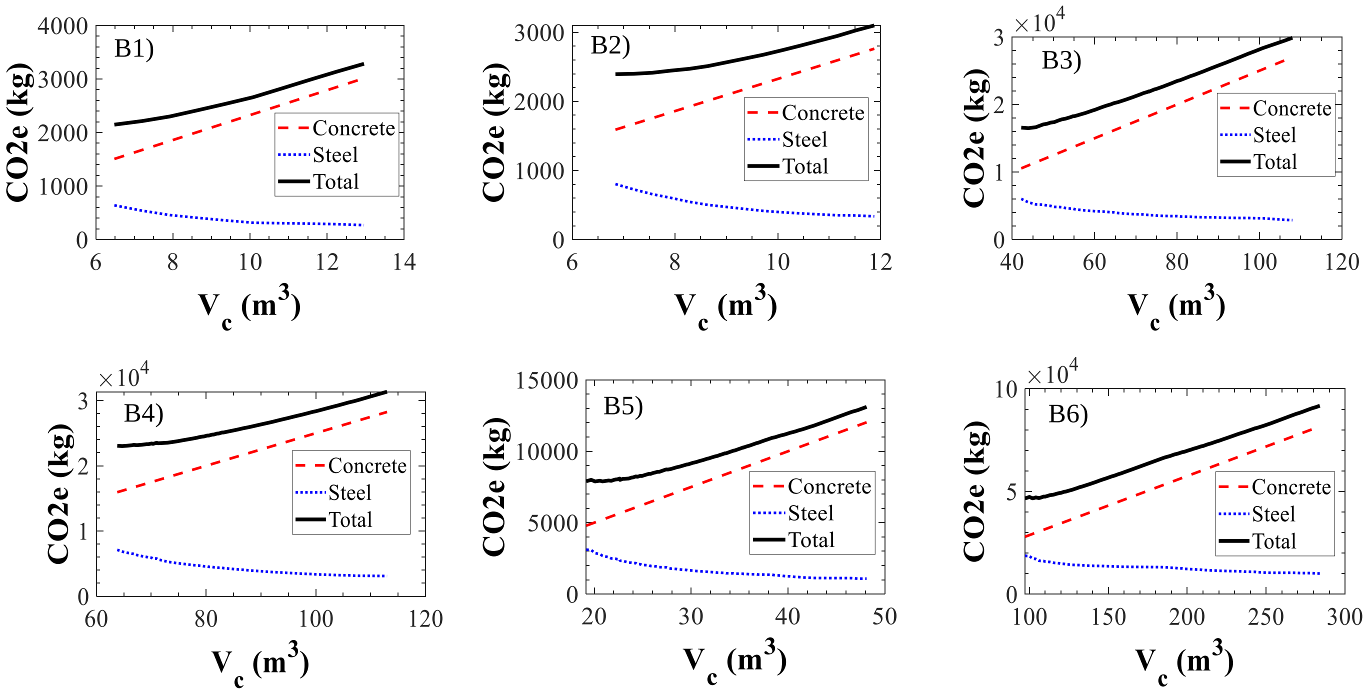

Fig. 7: $V_c(\boldsymbol{x})$ versus embodied carbon of RC frames Pareto optimal solutions under a typical UK concrete and reinforcing steel carbon factors scenario

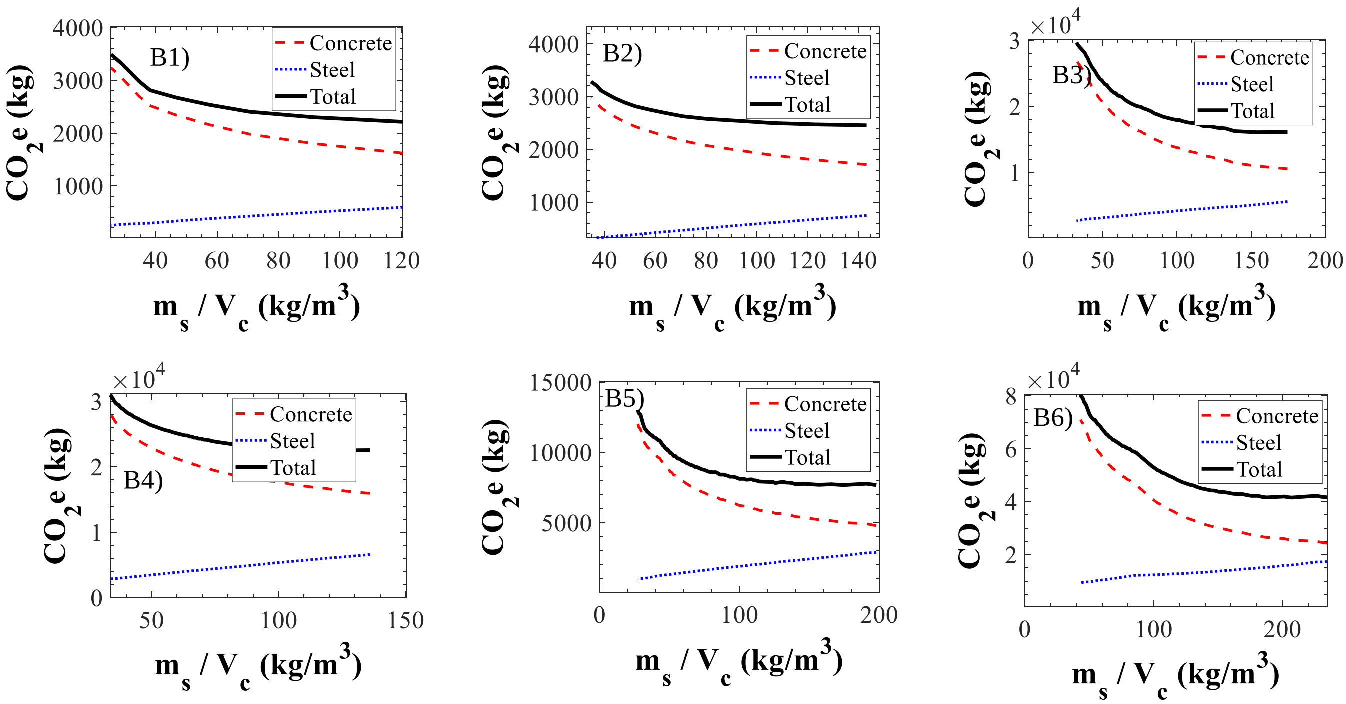

Fig. 8: $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ versus embodied carbon of RC frames Pareto optimal solutions under a typical UK concrete and reinforcing steel carbon factors scenario

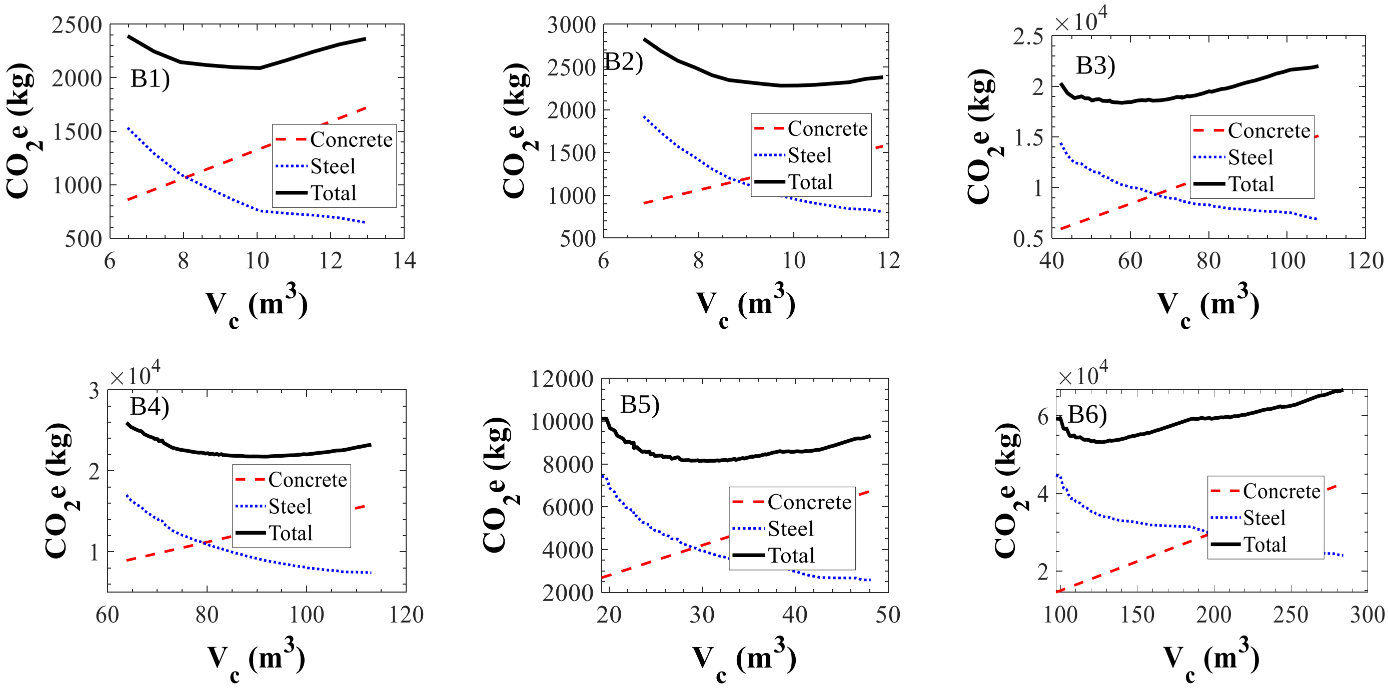

Fig. 9: $V_c(\boldsymbol{x})$ versus embodied carbon of RC frames Pareto optimal solutions under a green concrete and worldwide average steel reinforcement carbon factors scenario

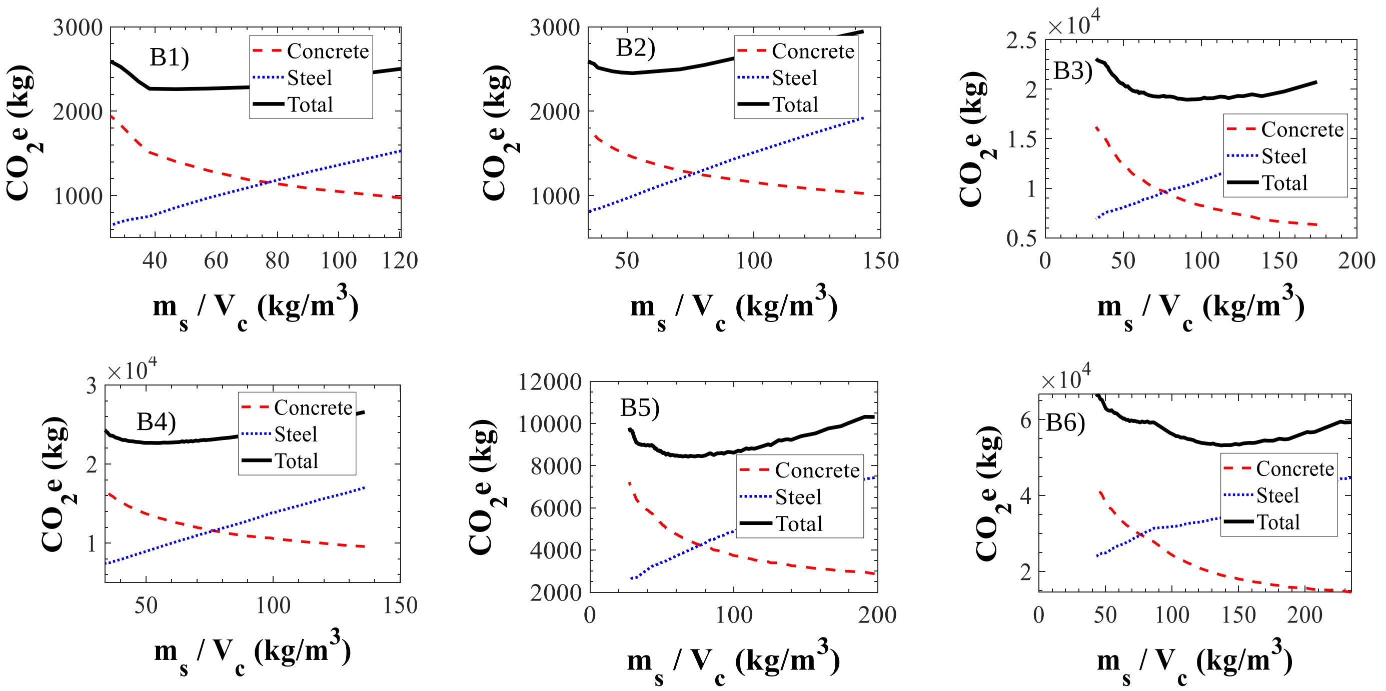

Fig. 10: $m_s(\boldsymbol{x})/V_c(\boldsymbol{x})$ versus embodied carbon of RC frames Pareto optimal solutions under a green concrete and worldwide average steel reinforcement carbon factors scenario

4.2 Parametric optimal designs

The previous section indicates the importance of carbon factor values in the determination of environmentally friendly design solutions of RC frames. In this section, a parametric study is conducted to derive more generic conclusions. To serve this goal, the R factor is introduced that represents the ratio of reinforcing steel to concrete carbon factors (i.e. $R = e_s/e_c$). For example, in the first scenario of the previous section, R ranges between 7 and 8. In the second scenario, R varies between 32 and 37. According to [3], for different material specifications and production routes globally, R may vary approximately between 2 and 80. Table 1 shows representative R values for different combinations of C25/30 concrete and steel reinforcement impact scenarios with regards to cement replacement ratios and steel production methods (i.e. EAF or BOF). Generally, R increases as the unit embodied carbon of steel reinforcement increases and the corresponding carbon of concrete decreases.

Table 1: R values for different concrete and steel reinforcement environmental impact scenarios [3]

Concrete Scenarios / **Rebar Scenarios**	**Lower bound UK C25/30 (70% GGBS) e_c = 0.056kgCO$_2$e/kg**	**Average UK C25/30 (25% GGBS) e_c = 0.100kgCO$_2$e/kg**	**Upper bound UK C25/30 (0% GGBS) e_c = 0.119kgCO$_2$e/kg**
Lower bound rebars (EAF production) e_s = 0.395kgCO2e/kg	7.1	4.0	3.3
Average UK rebars (EAF production) e_s = 0.76kgCO2e/kg	13.6	7.6	6.4
Upper bound rebars (BOF production) e_s = 3.970kgCO2e/kg	70.9	39.7	33.6

Using R, the objective function of Eq. (2) is re-written as shown below. Eq. (9) reveals that the optimal design solutions $\boldsymbol{x}^*$, minimizing $E(\boldsymbol{x})$, depend only on R and not the actual values of the material carbon coefficients e_c and e_s. In other words, any conclusions related to R are valid for any e_c and e_s values as long as $R = e_s/e_c$.

$$E(\boldsymbol{x}) = e_c \cdot (V_c(\boldsymbol{x}) \cdot \rho_c + m_s(\boldsymbol{x}) \cdot R) \quad (9)$$

In the following, the environmental impact $E(\boldsymbol{x})$ of the various Pareto optimal solutions of the RC frames is compared with the respective impact E_{Vmin} of the design solutions with minimum volume V_{min}. More particularly, Fig 11 presents the variation of $E(\boldsymbol{x})/E_{Vmin}$ carbon ratios against the volume ratios (*VR*), determined by Eq. 10, for the six RC frames and various *R* values. *VR* shows the relative position of the volumes $V(\boldsymbol{x})$ of the Pareto optimal design solutions between the minimum V_{min} and maximum V_{max} volumes of the Pareto fronts as shown in Fig. 5 (i.e. *VR* = 0 reflects the design solution with minimum concrete volume in the Pareto front and *VR* = 1 represents the design solution with maximum volume in the Pareto front).

$$VR = \frac{V(x)-Vmin}{V\max-Vmin} \tag{10}$$

As seen in Fig. 11, for R ≤ 10, $E(\boldsymbol{x})/E_{Vmin}$ ratios remain above 1 for all Pareto front design solutions and for all RC frames B1 to B6. Hence, for these R values, the V_{min} designs offer always the most environmentally friendly solutions. However, for higher *R* values, there exist Pareto front solutions yielding $E(\boldsymbol{x})/E_{Vmin}$ carbon ratios smaller than unity or in other words more environmentally friendly solutions than the V_{min} designs. The potential reductions in embodied carbon, with respect to E_{Vmin}, are up to 10% for *R* = 20, up to 20% for *R* = 40 and even up to 40% for *R* = 80. Furthermore, interestingly, the *VR* values of the design solutions offering minimum environmental impact increase as *R* increases. Despite the similarity in responses, the extent of reductions with respect to E_{Vmin} varies considerably between the RC frames for a given *R* value. The same is the case with the *VR* values minimizing embodied impact. It is also interesting to note that, for high *R* values, the $E(\boldsymbol{x})/E_{Vmin}$versus *VR* relationships of the RC frames typically flatten around the areas of minimum values. This essentially means that there is a wide range of $V(\boldsymbol{x})$ values that can offer nearly optimal environmentally friendly solutions.

To generalise further the results of Fig. 11, Fig. 12a presents the variation of $E_{Vmin}/E(\boldsymbol{x}^*)$ ratios as a function of *R* for the different RC frames. The average ratios of all RC frames are also shown in the figure. $E(\boldsymbol{x}^*)$ represents the environmental impact of the most environmentally friendly design solution $\boldsymbol{x}^*$. Hence, the $E_{Vmin}/E(\boldsymbol{x}^*)$ ratios show directly the potential inefficiencies, in terms of environmental footprint, by adopting the minimum concrete solution as opposed to the minimum carbon solution in the structural design of RC frames. It is shown that on average for *R* values up to 10, E_{Vmin} is indeed the minimum possible environmental impact of the RC frames. For higher *R* values, however, the environmental inefficiency of adopting the minimum concrete solutions increases almost linearly with *R*, but with different rates for the various RC frames. For *R* = 40, inefficiencies range between 10% and 30% with an average of 20%. For *R* = 80, excessive environmental impact between 25% and 60%, with an average of 40%, may be generated by selecting to minimize volume rather than embodied carbon.

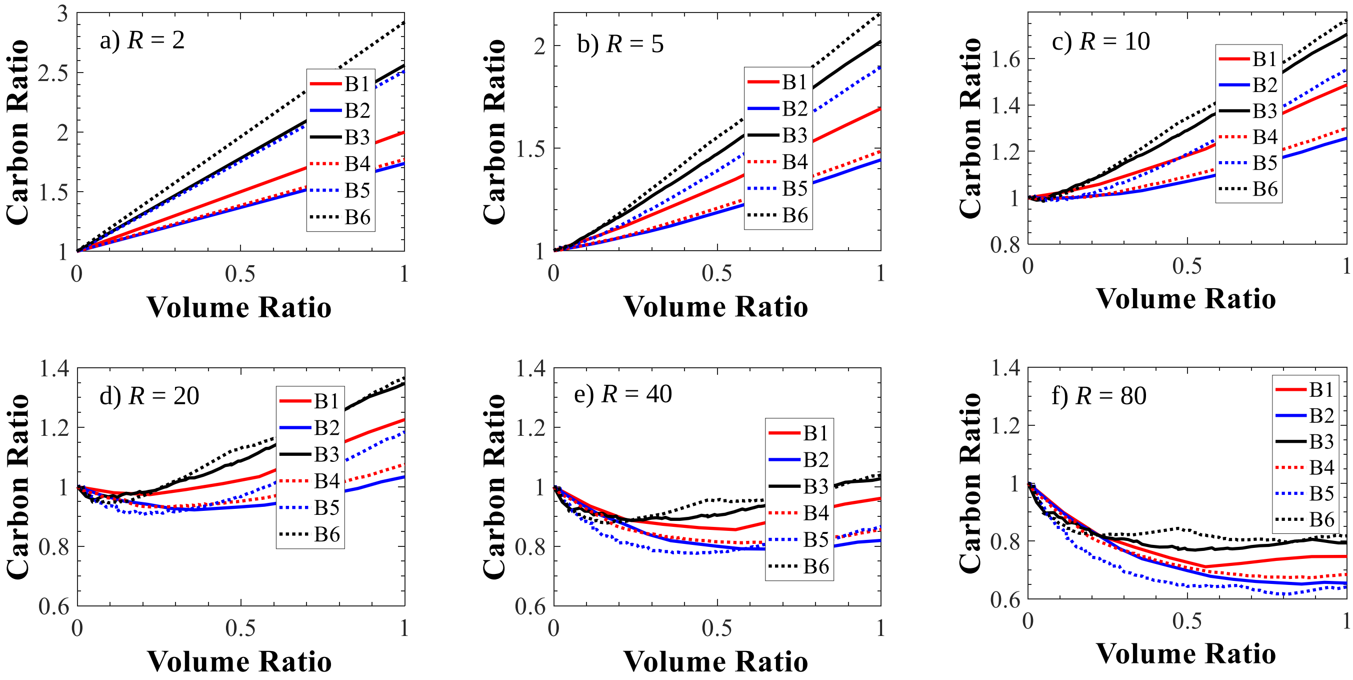

Fig 11: $E(\boldsymbol{x})/E_{Vmin}$ vs *VR* of the RC frames for different *R* values

Figure 12b sheds light into the contributions of concrete to the total embodied carbon of the most environmentally friendly RC frames as a function of *R*. The remaining embodied carbon comes from reinforcing steel. Expectedly, the contribution of concrete decreases as *R* increases. For *R* = 2, concrete dominates by contributing on average 88% to the total embodied carbon. This percentage drops to 63% for *R* = 10, where minimum concrete volume still governs optimal designs. The average contribution of concrete drops even further to 50% for *R* = 40 and 43% for *R* = 80. The latter observations partially explain why minimum volume does not control the optimal designs for higher *R* values.

Fig 12c presents the variation of the optimal *VR* ratios of the $\boldsymbol{x}^*$ solutions minimizing embodied carbon as a function of *R*. As expected, the optimal *VR* value is equal to 0 (i.e. minimum concrete solutions) for *R* values smaller than 10, approximately. For higher *R* values, the optimal volumetric ratios increase significantly and reach on average the value of 0.5 for *R* = 40 and 0.75 for *R* = 80. It is also noted that the optimal volumetric ratios, for given *R* values, vary significantly between the various RC frames.

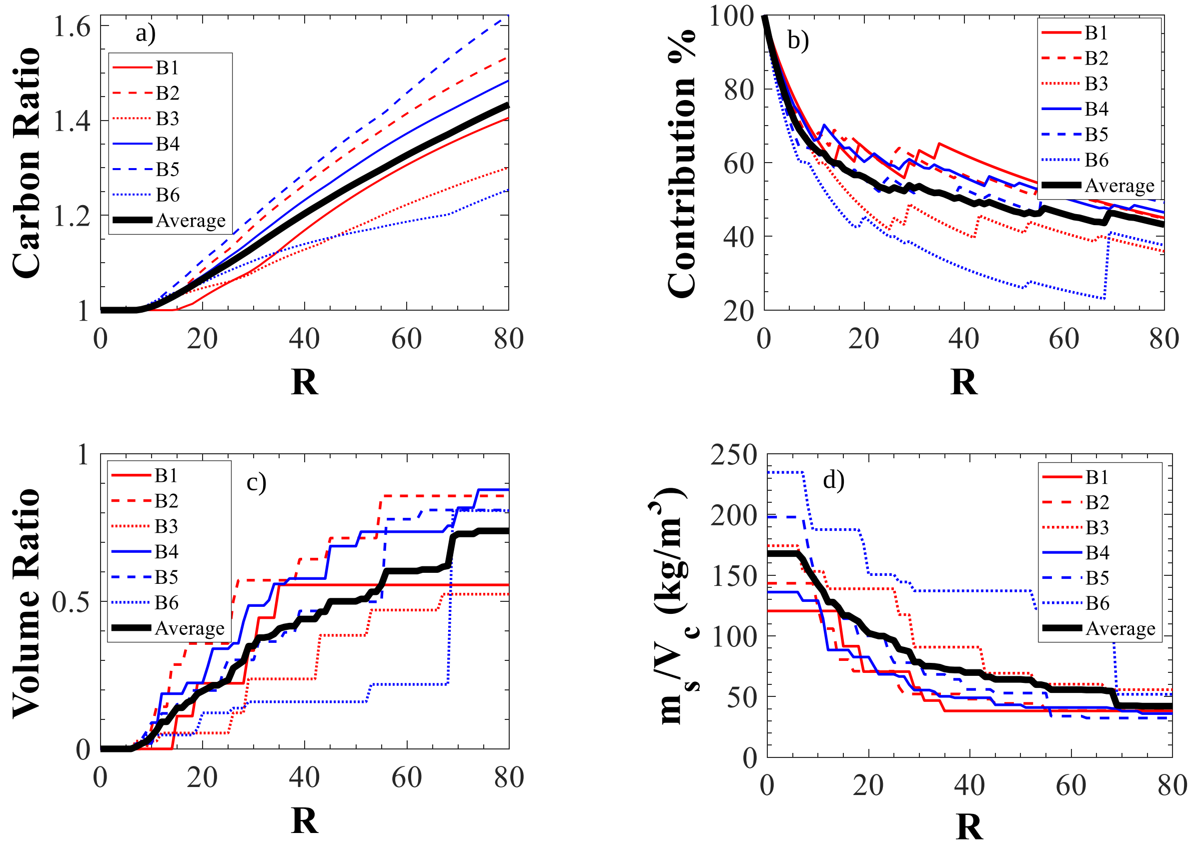

Fig 12: a) $E_{Vmin}/E(\boldsymbol{x}^*)$; b) concrete contribution to total carbon; c) optimal *VR*; d) optimal $m_s(\boldsymbol{x}^*)/V_c(\boldsymbol{x}^*)$ versus *R* for different RC frames and average values

Finally, Fig 12d presents the optimal $m_s(\boldsymbol{x}^*)/V_c(\boldsymbol{x}^*)$ ratios of the design solutions minimizing embodied carbon of the RC frames, as a function of *R*. It is observed that these ratios vary significantly with *R*. For *R* = 2, they range between 125kg/m^3 and 235kg/m^3 with an average value of 175kg/m^3, approximately. On the other end, for *R* = 80, the optimal $m_s(\boldsymbol{x}^*)/V_c(\boldsymbol{x}^*)$ ratios vary between 35kg/m^3 and 55kg/m^3 with an average value of 45kg/m^3. It is also observed that the optimal $m_s(\boldsymbol{x}^*)/V_c(\boldsymbol{x}^*)$ ratios vary largely among the various RC frames especially for small *R* values. The previous observations clearly point out that the common misconception assuming fixed $m_s(\boldsymbol{x}^*)/V_c(\boldsymbol{x}^*)$ ratios in optimally designed RC frames is false. On the contrary, optimal $m_s(\boldsymbol{x}^*)/V_c(\boldsymbol{x}^*)$ ratios in RC frames are case-specific and strongly dependent on *R* values.

Conclusions

The ongoing climate change requires drastic measures to reduce anthropogenic greenhouse gas emissions. The carbon efficient design of RC frames is expected to play a significant role in this direction. In standard engineering practice, designers often aim to minimize the amount of concrete and subsequently the volume of RC frames, by reducing the size of member cross-sections. This is done either for architectural reasons (i.e. to produce more elegant and aesthetically pleasing structures and to increase the usable space in buildings) or because it is assumed that it drives to more economic and environmentally friendly structures.

The current study, for first time, investigates the latter assumption by comparing the environmental impact of RC frames designed for minimum amount of concrete against designs targeting directly to minimize embodied carbon. To serve this goal, six realistic 3D RC frames are optimally designed for various carbon factor values of concrete and rebars.

It is found that the ratio of the carbon factor of rebars to concrete *R* plays a key role in the comparison of minimum volume and embodied carbon designs. More specifically, it is shown that the optimal designs for the two objectives practically coincide for $R \leq 10$. This is a useful conclusion since, for these R values, designers may indeed achieve to minimize embodied carbon by minimizing the volume and cross-sections of RC frames. However, for R values greater than 10, the minimum volume designs are not optimal in terms of environmental footprint. Instead, they produce, on average, 10% more carbon for *R* = 20, 20% for *R* = 40 and 40% more carbon for *R* = 80 than the optimal carbon designs. Hence, designers shouldn't be aiming at simply minimizing volume and cross-sections in RC frames to achieve minimum environmental impact for higher *R* values. Furthermore, they should be aware that minimizing the volume of RC frames for aesthetics and usable space comes with an additional carbon price when *R* exceeds approximately 10.

The current study also sheds light into the mechanisms that make minimum volume designs to separate from minimum carbon designs. As *R* increases, reinforcing steel becomes more carbon intensive compared to concrete. At the same time, reducing concrete below a certain amount drives to a sharp increase in the steel reinforcement required to satisfy design constraints. As a result, it becomes less and less carbon efficient to reduce the amount of concrete volume as *R* increases.

As a final observation, it is noted that the density of steel reinforcement in concrete for the most carbon efficient RC frames designs does not only depend on *R*, but it is also rather case-study specific. Hence, it is not proper to make generic conclusions regarding the optimal density of steel reinforcement in environmentally friendly RC frames.

Closing, it is important to emphasize that the current study focuses solely on RC frames. Its findings cannot be generalized to other structural systems/members in RC structures (e.g. slabs, walls, wall-frame systems) since the trade-offs between concrete and reinforcement quantities may vary. Hence, future studies are required to compare designs for minimum amount of concrete and embodied carbon in other RC structural members and systems.

References

1. IPCC (2021) Climate change 2021: The physical science basis. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, USA
2. IEA (2020) Energy technology perspectives 2020. International Energy Agency
3. IStructE (2021) How to calculate embodied carbon. The Institution of Structural Engineers, UK
4. Jones C (2019) ICE Database V3.0 Beta. Retrieved from https://circularecology.com/embodied -energy-and-carbon-footprint-database.html
5. Purnell P, Black L (2012) Embodied carbon dioxide in concrete: Variation with common mix design parameters. Cem Concr Res 42: 874-877
6. Lagaros ND (2020) The environmental and economic impact of structural optimization. Struct Multidiscip O 49:1047-1066
7. Lagaros ND (2014) A general purpose real-world structural design optimization computing platform. Struct Multidiscip O 49:1047-1066

8. Sarma KC, Adeli H (1997) Cost optimization of concrete structures. J Struct Eng 124:570-578
9. Paya-Zaforteza I, Yepes V, Gonzalez-Vidosa F, Hospitaler (2008) Multi-objective optimization of concrete frames by simulated annealing. Comput Aided Civ Inf 23: 596-610.
10. Paya-Zaforteza I, Yepes V, Hospitaler A, Gonzalez-Vidosa F (2009) CO_2-optimization of reinforced concrete frames by simulated annealing. Engineering Structures 31: 1501-1508.
11. Yeo D, Gabbai R (2011) Sustainable design of reinforced concrete structures through embodied energy optimization. Energy and Buildings 43: 2028-2033.
12. Camp CV, Huq F (2013) CO2 and cost optimization of reinforced concrete frames using a big bang-big crunch algorithm. Engineering Structures 48: 363-372.
13. Medeiros G, Kripka M (2014) Optimization of reinforced concrete columns according to different environmental impact assessment parameters. Engineering Structures 59: 185-194.
14. Yeo D, Potra F (2015) Sustainable design of reinforced concrete structures through CO_2 emission optimization, Journal of Structural Engineering-ASCE 141 (2015) B4014002-1:7.
15. Eleftheriadis S, Duffour P, Greening P, James J, Stepheson B, Mumovic D (2018) Investigating relationships between cost and CO2 emissions in reinforced concrete structures using a BIM-based design optimisation approach. Energy and Buildings 166: 330-346
16. Mergos PE (2018) Contribution to sustainable seismic design of reinforced concrete members through embodied CO2 emissions optimization. Struct Concrete 19:454–462.
17. Mergos PE (2018) Seismic design of reinforced concrete frames for minimum embodied CO2 emissions. Energ Buildings 162:177–186
18. Zhang X, Wang F (2023) Influence of parameter uncertainty on the low-carbon design optimization of reinforced concrete continuous beams. Structural Concrete 24: 855-871
19. Mergos PE (2023) Sustainable and resilient seismic design of reinforced concrete frames with rocking isolation on spread footings. Engineering Structures 292: 116605
20. Kaveh A, Sabzi O (2011) A comparative study of two metheuristic algorithms for optimal design of planar RC frames. Int J Civ Eng 9: 193-206
21. Akin A, Saka MP (2015) Harmony search algorithm based optimum detailed design of reinforced concrete plane frames subject to ACI 318-05 provisions. Comput Struct 147:75-95
22. Mergos PE (2018) Efficient optimum seismic design of reinforced concrete frames with nonlinear structural analysis procedures. Struct Multidiscip O 58:2565-2581
23. Rakici E, Bekdaş G, Nigdeli SM (2020) Optimal cost design of single-story reinforced concrete frames using Jaya algorithm. CHSA 2020: Proceedings of 6th International Conference on Harmony Search, Soft Computing and Applications pp 179-186
24. Kaveh A, Izadifard RA, Mottaghi L (2020) Optimal design of planar RC frames considering CO_2 emissions ssing ECBO, EVPS and PSO metaheuristic algorithms. J Build Eng 28: 101014
25. Fadaee MJ. Grierson DE (1996) Design optimization of 3D reinforced concrete structures. Struct. Optimization 12:127-134
26. Govindaraj V, Ramasany JV (2007) Optimum detailed design of reinforced concrete frames using genetic algorithms. Eng Optimiz 39:471-494
27. Sharafi P, Muhammad NS, Hadi M (2012) Heuristic approach for optimum cost and layout design of 3D reinforced concrete frames. J Struct Eng 138:853-863
28. Kaveh A, Behnam AF (2013) Design optimization of reinforced concrete 3D structures considering frequency constraints via a charged system search. Sci Ira Trans A 20:387-396
29. Esfandiari MJ, Urgessa GS, Sheikholarefin S, Dehghan Manshadi SH (2018) Optimum design of 3D reinforced concrete frames using the DMPSO algorithm. Adv Eng Softw 115:149-160
30. Dehnavipour H, Mehrabani M, Fakhriyat A, Jakubczyk-Galczynska A (2019) Optimization-based design of 3D reinforced concrete structures. J Soft Comput Civ Eng 3:95-106
31. Martins A, Simões L, Negrão J, Lopes A (2020) Sensitivity analysis and optimum design of reinforced concrete frames according to Eurocode 2. Eng Optimiz 52:2011-2032
32. Mergos PE (2021) Optimum design of 3D reinforced concrete building frames with the flower pollination algorithm. J Build Eng 44:102935
33. Mergos PE (2022) Surrogate-based optimum design of 3D reinforced concrete building frames to Eurocodes. Developments in the Built Environment 11:100079
34. Halliwell E (2022) How to cut carbon in reinforcement. Concrete Quarterly 281:28-35. The Concrete Centre, UK
35. CEN (2000) Eurocode 2: Design of concrete structures. Part 1-1: General rules and rules for buildings, Brussels: European Standard EN 1992-1-1
36. CEN (2002) Eurocode 0: Basis of Structural Design. Brussels: European Standard EN 1992:2002
37. CEN (2004) Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings, Brussels: European Standard EN 1990-1.
38. CSI (2022) https://www.csiamerica.com/products/sap2000

39. CSI (2016) Concrete frame design manual: Eurocode 2-2004 with Eurocode 8-2004 for SAP2000. ISO SAP091415M29 Rev. 1, USA.
40. Moss R, Brooker O (2006) How to design concrete structures using Eurocode 2: Beams. The Concrete Centre, Surrey, UK
41. Mergos PE (2024) Benchmark problems in optimum structural design or 3D reinforced concrete frames. J Build Eng 91:109554