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Parametric study on the decarbonization potential of structural system and concrete mix design choices for mid-rise concrete buildings

Hisham Hafez [ORCID] · **Petar Bajić · Stanislav Aidarov ·
Xhemsi Malija · Michal Drewniok · Phil Purnell ·
Nikola Tošić**

Abstract Mid-rise reinforced concrete buildings are projected to continue being the predominant typology for urban development. Thus, reducing the carbon footprint of such buildings is critical for achieving a sustainable built environment. Reducing the amount of concrete and steel in a building through structural and mix design optimization is identified as a primary resource efficiency strategy. This paper is among the first to present evidence of the decarbonization potential of these dematerialization strategies on a building level. The study combines structural design choices such as slab system design, steel reinforcement optimization and span width with materials-based strategies, such as low binder concrete and low-carbon binders. For each scenario, material quantities are calculated following design prescriptions by EN1992–1–1 while state-of-the art life cycle inventory data are adopted to calculate the carbon footprint. Results show that shifting towards more efficient structural systems (i.e., waffle slab system) could save up to 20% of the carbon footprint on the building level compared to more traditional systems, such as slab on beams and flat slabs. In addition, reducing the spans from 7.5 to 5 m can save up to 20% more. Finally, the use of low-clinker cement in low-binder concrete can save another 50% in terms of CO_2 impact per built-up area. Realistically, results of the case study concluded that implementing these three strategies could reduce the typical 232 kg CO_2e/m^2 value of the carbon footprint of structural elements of a mid-rise building up to only 58 kg CO_2e/m^2, i.e., a four-fold reduction.

H. Hafez (✉) · M. Drewniok · P. Purnell
School of Civil Engineering, University of Leeds,
Leeds LS2 9JT, UK
e-mail: h.hafez@leeds.ac.uk

M. Drewniok
e-mail: m.p.drewniok@leeds.ac.uk

P. Purnell
e-mail: p.purnell@leeds.ac.uk

P. Bajić · N. Tošić
Civil and Environmental Engineering Department,
Universitat Politècnica de Catalunya–BarcelonaTech
(UPC), Jordi Girona 1–3, 08034 Barcelona, Spain
e-mail: petar.bajic@upc.edu

N. Tošić
e-mail: nikola.tosic@upc.edu

S. Aidarov
Project and Construction Engineering Department,
Universitat Politècnica de Catalunya–BarcelonaTech
(UPC), Av. Diagonal 647, 08028 Barcelona, Spain
e-mail: stanislav.aidarov@upc.edu

X. Malija
Structural Concrete Laboratory, IBETON, ENAC,
CH-1015 Lausanne, EPFL, Switzerland
e-mail: xhemsi.malija@epfl.ch

1 Introduction

The embodied environmental impact of the business-as-usual construction practices, including materials and construction processes contributes up to 11% of the global carbon emissions [1]. Most of this impact (approximately 60%) is attributable to the 14 billion tons of concrete produced annually [2]. Approximately 400 million tons of steel rebars are produced annually for use in reinforced concrete contributing a further 1.5% share of the global carbon emissions [3]. The current global building stock, for residential and service buildings specifically, is predominantly comprised of reinforced concrete buildings [4]. Moreover, the unavoidable need to provide affordable housing for the growing population, especially in the Global South, is projected to increase the demand for concrete globally by at least 25% by 2050 [5]. A recent study of 769 buildings in Europe concluded that the lowest, average, and highest carbon footprint for concrete frame buildings is 400, 650 and 1200 kg CO_2e/ m^2 of built-up area, respectively [6]. Another paper reported proximate values of 420, 750 and 1350 kg CO_2e/m^2, respectively, based on a survey of 95 case studies of reinforced concrete residential buildings globally [7]. The high variance in the reported carbon benchmark of reinforced concrete buildings could be attributed mainly to the significant impact of structures with irregular floor plan geometries especially in office buildings [8]. For modular mid-rise buildings, a survey of over 600 buildings in Europe concludes that the current best practice has a carbon footprint between 270 and 367 kg CO_2e/m^2 [9]. Significantly lower values (160 and 137 kg CO_2e/m^2) were reported as target values for mid-rise reinforced concrete buildings in Canada and the U.S. according to Hart et al. [10] and Arceo et al. [11] respectively.

Accordingly, mid-rise concrete frame buildings were chosen as the focus of this study because it has the highest decarbonization potential [12] and is the most common urban housing typology globally [13]. To analyse decarbonization routes, it is required to establish that the embodied carbon of buildings is a sum product of the material intensity, a metric that normalizes the quantities (mass) of the materials used per unit floor area of a building and carbon intensity, which is the embodied carbon per unit of each of the materials [14]. Accordingly, decarbonization strategies are split into demand-based ones targeting the reduction of the material intensity and supply-based ones for low-carbon materials.

The material intensity of concrete and steel is determined based on the sizing of the different elements of the building to satisfy the structural design requirements. This study will focus only on the structural components (concrete and steel) of reinforced concrete buildings as they constitute 80% and 90% of the material and carbon intensity respectively [15]. Another reason is that this study aims to present global perspectives while non-structural components vary widely among different climate zones depending on insulation requirements [16]. There are three main strategies discussed in the literature to reduce the volume of concrete and steel mid-rise reinforced concrete buildings. The first is slab system and span width selection since slabs contribute more than 50% to the concrete volume in a building [17]. A case study also showed that precast hollow core slabs are proven to optimize the material use for spans larger than 10 m [18].

For more commonly used cast in-situ systems, an extensive study by Drewniok [19] concluded that for the same span (7.5 m) a waffle slab system choice could reduce 50% and 75% the volume of a slab compared to two-way slab-on-beam and flat slab systems, but the comparison did not include smaller spans. The second is the use of the yield line method (YLM) using a limit state theory [20]. Previous work showed that applying the method could lead to potential reduction in the steel reinforcement of a slab [21]. Finally, the third strategy is the potential reduction in the dimensions of structural concrete elements as a result of specifying higher concrete strength. Although this was proven to be effective in bridge piers [22] and high-rise buildings [23], minimum code-specified dimensions could render this strategy ineffective in mid-rise building elements.

Regarding the carbon-intensity reduction strategies, the cement and concrete industrial decarbonization roadmaps published shows a consensus that 60% of the embodied carbon savings depend on high-tech strategies such as fuel switching, decarbonized

electricity grids as well as carbon capture, utilization, and storage (CCUS) [2, 24, 25]. However, several critics have highlighted that the role of these technologies in the decarbonization targets aspired for 2050 is realistically minimal due to the high capital investment [26], technology readiness levels [27] and limited resources [28].

A recent review of nine roadmaps concludes that the most probable decarbonization strategies are concrete mix design optimization and clinker substitution [29]. First, the use of water reducing admixtures and optimized particle packing of the solid components of a concrete mix are both effective in reducing the binder intensity (the amount of binder required to achieve 1 MPa of 28 days compressive strength) by up to 50% [30]. Depending on the type of binder used, this strategy could reduce the carbon intensity (the carbon footprint per unit volume) of concrete by up to 40% [31]. Second, the carbon intensity of the binder itself could be lowered through the reduction of clinker content using supplementary cementitious materials (SCMs) [32]. Novel mineral waste-based SCMs are being considered but yet to make a market impact [33, 34]. Nonetheless, with a declining supply of the commonly used SCMs (fly ash and slag), the use of limestone calcined clay cement (LC^3) is a more sustainable solution [35]. Depending on the calcined clay reactivity and replacement levels, LC^3 concrete could exhibit comparable compressive strength and durability compared to a reference OPC (Ordinary Portland Concrete) concrete as well as up to 30%

reduction in the carbon footprint per unit volume [36]. Although the reduction in binder and clinker content in concrete is reported to reduce the carbon intensity of concrete by a combined 70%, there is a gap in the literature for studying the resulting carbon footprint reduction on a building level.

With the above-mentioned in mind, this paper focuses on code compliant, commercially-ready decarbonization strategies related to the decisions beyond the conceptual design stage. The paper proceeds as follows. Section 2 lays out the definition of the case study analysed and the strategies for reducing material and carbon intensity. Section 3 presents and discusses the results, including the slab system and steel reinforcement design, the effect of concrete strength and low-carbon concrete, Finally, Sect. 4 concludes the paper.

2 Case study definition

Within this study, a building with 35.0×15.0 m slabs supported by columns with square cross-sections is designed, Fig. 1. The main objective is to assess, for a geometrically modular mid-rise reinforced concrete building, the relative impact of seven strategies—related to decisions beyond the conceptual design stage—for decarbonization of a concrete building on structural and concrete mix design as discussed in the following subsections. The 288 different alternatives

Fig. 1 Isometric view of analysed structures: **a** five storey; **b** ten storey
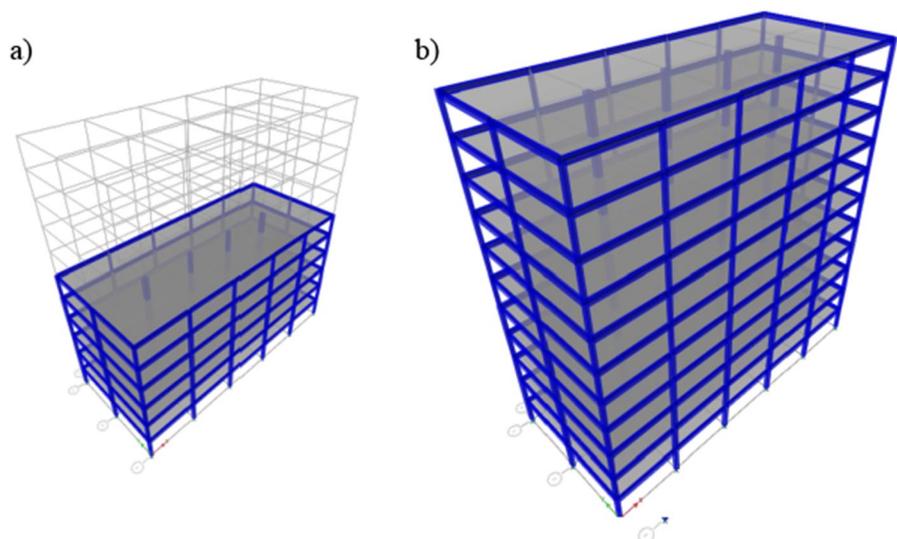
considered for each of the strategies are shown in Fig. 2.

2.1 Material intensity reduction strategies

For all alternatives, to calculate the building-level concrete and steel material intensities, structural analysis and design have been performed using CSi Etabs 18 Ultimate, CSi SAFE 2016 Post Tensioning [37] and in-house developed design spreadsheets. All structural elements have been designed to use the least possible volume of materials, while still satisfying the requirement of both ultimate and serviceability limit states (ULS and SLS, respectively). The loads specified in EN 1991–1–1 (EC1) for residential buildings [38] were taken as a reference to compute the load combinations for ULS and SLS. Self-weight of the structure was calculated by the software CSi Etabs and CSi Safe [37] (q_{SW}) with the assumed weight of reinforced concrete of 25 kN/m^3. Additionally, a superimposed dead load (q_G) and live load (q_Q) of 2.5 and 2.0 kN/m^2, respectively, were adopted to act as distributed loads on slabs. Moreover, a line of load on the slab perimeter of 2.0 kN/m was considered. Load partial factors $\gamma_G = 1.35$ and $\gamma_Q = 1.50$ were adopted to estimate the design load at ULS: $q_{Sd} = \gamma_G \cdot (q_{SW} + q_G) + \gamma_Q \cdot q_Q$. In turn, the quasi-permanent load combination ($q_{k,\psi2} = q_{SW} + q_G + \psi_2 \cdot q_Q$; $\psi_2 = 0.3$)

for residential buildings was taken into account for deflection and crack width checks. Structural analysis and design of the superstructure have been performed according to EN1992–1–1:2004 (EC2) for concrete structures [39], while the substructure was designed according to EN 1997–1 (EC7) for geotechnical design [40]. It was assumed that EC2 provisions are valid for all considered concretes, both the reference and low-carbon concrete.

2.1.1 Slab system design

As shown in Figs. 3 and 4, three different types of horizontal load-bearing members have been analysed: 1) slabs directly supported on columns (flat slabs) with perimeter beams as shown in Fig. 1, 2) two-way slabs supported on beams, and 3) waffle slabs. Although the number of stories is not typically a design variable but a constraint, in this work it is considered as a complementary part of the study to investigate its role in the potential reduction of material volumes of a building per built area. Accordingly, structures of two different heights (5 and 10 storey high) are considered as shown in Figure. Storey height is fixed equal to 3.25 m in all the scenarios. For each case, columns have been placed in the intersections of the grid axes and the foundation system has been adopted as a raft (mat) foundation slab, with
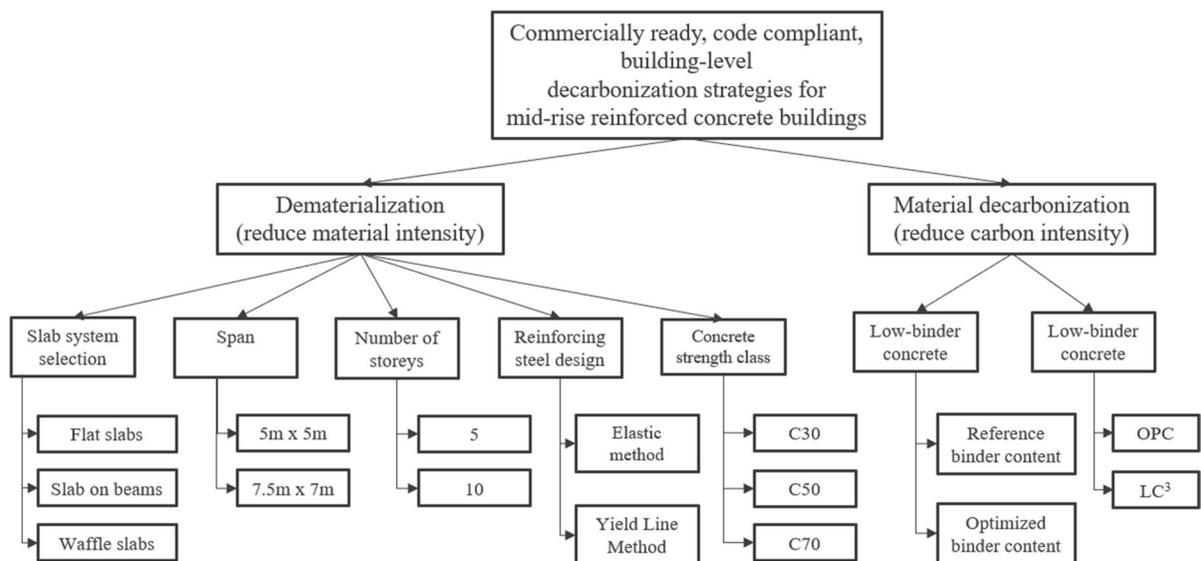

Fig. 2 A schematic of the 7 decarbonization strategies and 288 alternatives generated within this case study
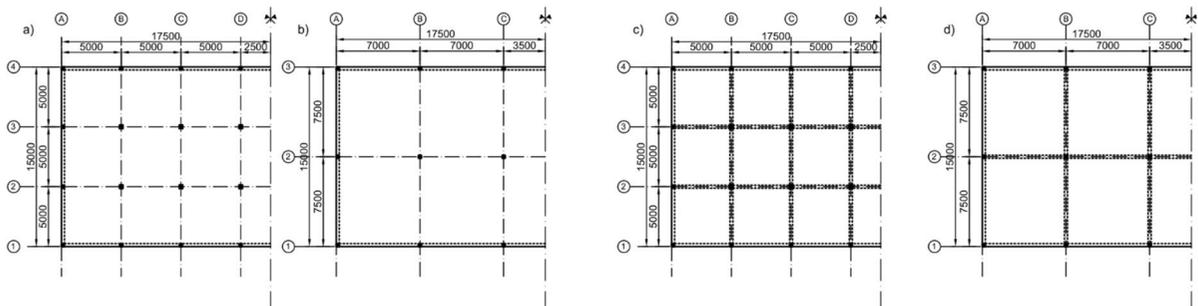
Fig. 3 Floor system **a** flat slab 5.0×5.0 m² layout; **b** flat slab 7.0×7.5 m² layout; **c** slab on beams 5.0×5.0 m² layout; **d** slab on beams 7.0×7.5 m² layout
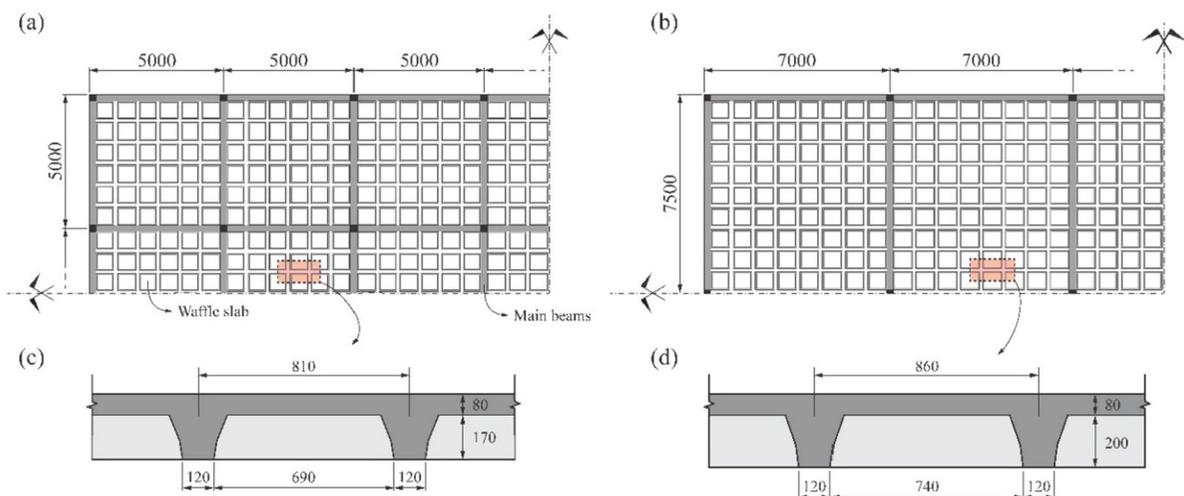
Fig. 4 Floor system **a** waffle slab 5.0×5.0 m² layout; **b** waffle slab 7.0×7.5 m² layout; **c** waffle slab 5.0×5.0 m² cross-section; waffle slab 7.0×7.5 m² cross-section

its dimensions depending on the geotechnical design. A soil subgrade modulus of 6000 kN/m²/m has been assumed for the purpose of this study as representing clayey soil with allowable stress $q_a = 200$ kPa and allowable settlement of 50 mm [41].

2.1.2 Steel reinforcement design

Considering that the horizontal elements (slabs and beams) have a major influence on the overall amount of materials required, the results obtained by means of linear elastic finite element analysis (LEFEA) are compared with the design performed using the yield line method (YLM) [42, 43]. For the elastic design of the slab, two different reinforcement strategies for the

bottom zone have been considered, the first using the same layout of the YLM (unoptimized elastic) and the second by placing reinforcements in strips (optimized elastic). The width of the strip was taken equal to 25% of the perpendicular span on each side of the column. The top zone reinforcement has the same layout for all design approaches. Additional punching reinforcement is necessary only over the internal columns as the perimeter beam is present in all slab structural systems. Typically, the reinforcement detailing would depend on the diameter chosen for the rebars, which also influences the anchorage length and splices. To allow for generic results, there were no specific reinforcement layouts adopted in any of the designs, but 30% extra reinforcement was assumed for all design

alternatives to account for the steel detailing. Reinforcement layouts considered in this study are shown in Fig. SF1–SF-4 in the supplementary information document.

2.1.3 Concrete strength

The mechanical properties of the materials used in the current study comply with the requirements of EC2 [39]. As a result, the characteristic yield strength of reinforcing steel in tension (f_{yk}) of 500 MPa is assumed. The characteristic cylinder compressive strengths (f_{ck}) is assumed as a variable (i.e., the concrete strength classes C30/37, C50/60, and C70/85). Moreover, an option to use different concrete classes for horizontal and vertical structural elements has also been investigated. The concrete class used for columns is assumed equal to or one class higher than the class used for slabs (i.e. a combination of C30/37 slabs and C50/60 columns was considered, but a combination of C30/37 slabs and C70/85 columns was not).

2.2 Carbon intensity reduction strategies

2.2.1 Low binder concrete

As established, this paper aims at judging the relative decarbonization potential of a combination of strategies for a mid-rise cast-in-situ reinforced concrete building. For materials scope, as shown in Fig. 2, there are two main strategies, the first of which is to reduce, for each of the three target strength classes (C30/37, C50/60, and C70/85), the binder content per concrete unit volume. Building on the concept of optimized particle packing of the solid volume fraction of concrete as well as the use of water reducing admixtures, the amount of binder (kg/m^3) could be reduced by up to 50% [44]. A more conservative binder content saving (30%) was achieved in the mix designs for this paper by reviewing the trends in more than 500 concrete mixes from a previous publication [45]. The mix design proportions of the studied alternatives in shown in Table 1.

2.2.2 Low-carbon binder

The second strategy to reduce the carbon footprint of the reinforced concrete materials is to use low-carbon

Table 1 Secondary LCA inventory data for the materials and processes included in the case study

Scenario	Strength class (MPa)	Binder	Water	Coarse	Fine	SP				
		kg/m^3 of concrete								
Baseline	30	320	175	1015	870	0				
	50	400	165	1065	783	1.05				
	70	500	185	1145	600	1.5				
Low-binder	30	225	123	1158	757	0.45				
	50	280	116	1062	792	2.33				
	70	350	130	1051	855	3.75				
								Reinforcing Steel		Slab system (formwork, mixing and placing)
		OPC					Large truck	Average	Solid	Flat
GWP	LC^3									21.96
(kg CO$_2$e/unit)	0.53	0.83	0.0001	0.02	0.01	1.84	0.15	0.84	35.18	
										Waffle
										21.05
Unit	kg						tonne.km	kg	m^3	
Reference	[47]							[50]	[51]	

binder. The baseline binder is assumed to be OPC, and LC^3 is proposed as a low-carbon solution. An established method to calculate the environmental impact for a concrete building is to study resource use and emissions attributed, through a life cycle assessment (LCA) [46]. The LCA scope selected for this study is Cradle-to-Site, which is typical of building-level LCA and includes all the emissions and resource use resulting from the production of the building material production, transportation, and construction processes. This means that the environmental impact associated with the operation/use of the building and its end-of-life is considered to be out of scope including the potential carbon sequestration from the atmosphere, which combined amount only to < 15% of the total embodied carbon of a building [47].

The functional unit (FU) selected is a unit built-up area of a building, which is usually calculated as the leasable area (minus the common areas and utilities) especially in whole life cycle building analyses, where operational carbon is also accounted for [48]. However, the comparison in this paper is limited to structural building components, so a unit built-up area is calculated as the net floor area (the floor area minus that of columns) multiplied by the number of storeys. It is assumed that all concrete alternatives exhibit the same durability performance to fulfil the 50 years' service life requirement. Concrete cover has been calculated for every structural element by considering concrete class and type of structural element as per requirements of EC2 [39]. Although higher carbonation rates are reported in the literature for LC^3 concrete compared to OPC, the higher resistance to chloride penetration accommodates the previous assumption of compatible service life between both binder types [49]. For the C30/37 concrete class, the concrete cover thickness is 30 and 35 mm for horizontal and vertical structural members respectively. In the case of higher concrete classes, C50/60 and C70/85, the thickness has been reduced by 5 mm. The minimum cover thickness for the foundations is 50 mm.

The second stage of an LCA is to prepare the inventory database, which is the quantities of materials and construction related environmental impact related to each scenario including the environmental impact of each of the concrete element constituents. Since decarbonization is the focus of this study, the only environmental impact indicator selected is Global Warming Potential (GWP), which indicates the equivalent carbon emissions of the studied scope. The source of the inventory data selected is literature-based and the transportation distances assumed for the concrete raw materials were chosen, similar to that between the concrete production and the construction site, as 50 km using a large truck. For reinforcing steel, the assumption is that all global supply of reinforcing steel is from electric arc furnaces [3] for which Fan and Friedmann report a global average of 0.84 kg CO_2e/kg [50]. There is a scarcity in the literature discussing the difference between the carbon footprint associated with the formwork and concrete casting processes between the different slab systems. The values reported by Paik and Na [51] are reported in Table 1 assuming a similar re-usability of formwork between the three systems under study, slab on beams, flat slabs, and waffle slabs. The summary of the carbon intensity for the mix designs for the proposed alternatives are shown in Table 1.

3 Results and discussions

3.1 Slab system design

Across all study scenarios, results showed that the essential portion of the concrete required corresponds to the horizontal elements: approximately 60% and 30% of the overall volume corresponds to the elevated slabs and foundation slab, respectively. As Fig. 5 shows, the concrete volumes do not change between the slab on beam and flat slab systems within the specified number of storeys (5–10) and spans (5–7.5 m). However, the use of a waffle slab solution allows reducing the required amount of concrete between 15 and 35% compared with the alternative of the same spans using flat slab or slabs on beams. Meanwhile, as seen in Fig. 5, the flat slab and slab on beams solutions provided similar overall results, in terms of volumes of concrete, as any decrease in the thickness of the slab is cancelled out by the concrete used for the beams. The error bars in Fig. 5 show the difference between average concrete volumes for individual structural element and the corresponding maximal/minimal volume between analyzed alternatives. A detailed summary of material quantities is given in Table S-1 in the supplementary information document.

Fig. 5 Average concrete volumes for considered scenarios
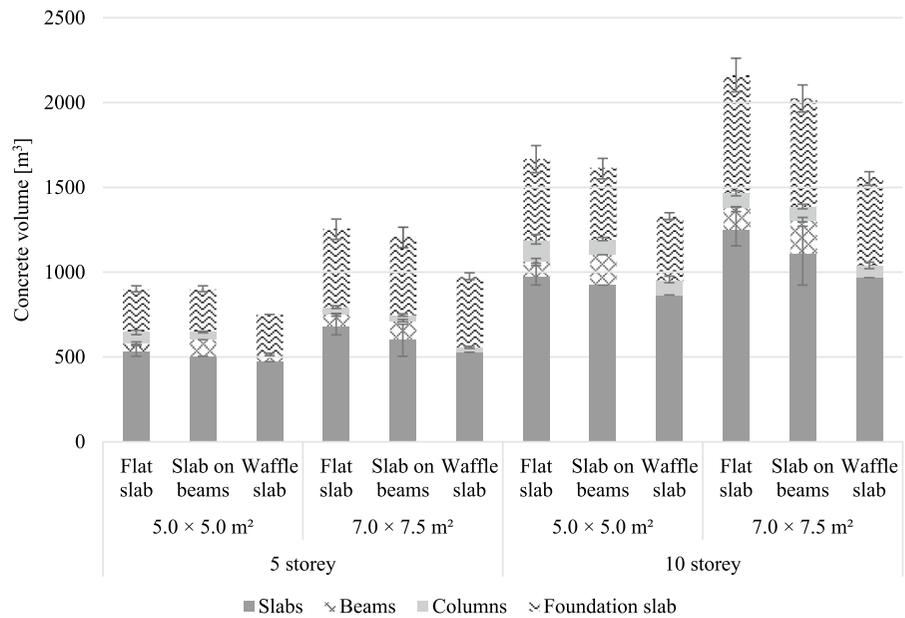
The material intensities (normalized material quantities) calculated from the case study confirm the first two findings of this paper. First, for the studied load cases, the use of a waffle slab reduces the concrete intensity of concrete and steel by an average of 20% compared to slab on beams and flat slab systems. Second, the reduction of the span width reduces the material intensity by further 20%. Hence, for a 10 storey building as seen in Fig. 6, the combined material intensity of a 5 m waffle slab system, which is 641 kg/m^2 (620 for concrete and 21 for steel) is approximately half that of a 7.5 m flat slab system. A validation of the values calculated in this study is that they fall between the upper and lower limits identified in the literature. As seen in Fig. 5, the lower limit for optimized mid-rise design by D'Amico and Pomponi [52] is approximately 500 kg/m^2 while the upper limit is the 1100 kg/m^2 from a survey by DeWolf et al. [53].

The main objective behind this study is to assess the decarbonization potential of the different dematerialization strategies. Accordingly, using the conventional OPC concrete mix as a baseline for the carbon intensity, the 10-storey building designed for a 7.5 m flat slab system carries a normalized carbon footprint of 210 kg CO_2e/m^2. As shown in Fig. 7, the dematerialization strategies discussed previously decrease the carbon footprint to approximately 125 kg CO_2e/m^2 when shifting to a 5 m waffle slab system. Since it

is a linear relationship with the material carbon intensity being constant, the 40% reduction in the material intensity resulting from a combination of the shift to a waffle slab and the reduction of the span from 7.5 to 5 m, results in a 40% reduction in the building level carbon intensity. As shown in Fig. 7, the improvement (reduction) in carbon footprint of waffle slabs over flat slabs and solid slabs is clearer in 7.5 m spans compared to the 5.0 m spans. Accordingly, the decision to design the case study to include only these 2 spans (5.0 and 7.5 m) is justified as the larger spans would only further validate the established trends between the three selected systems.

Another finding from this case study is that minimal (1–2%) variation is found in the carbon footprint on the building level between the 5 and 10 stories scenarios. The results agree with the outcome reported by Gan et al. [14], which states that unless a shift in structural system is needed (adding outrigger systems, transfer floors or changing the foundations system, etc.), the concrete volume increases in linear proportion with the built-up area. In fact, the carbon footprint of a high-rise building is less in a consequential scenario due to the savings from the land use to house the extra inhabitants compared to a low-rise building [54]. However, recent papers conclude that from an urban perspective, a mis-rise building might be optimum due to the social implications of the congestion resulting from the high-rise buildings as well as other

Fig. 6 Building level material intensity values for concrete and steel from this study compared against literature values
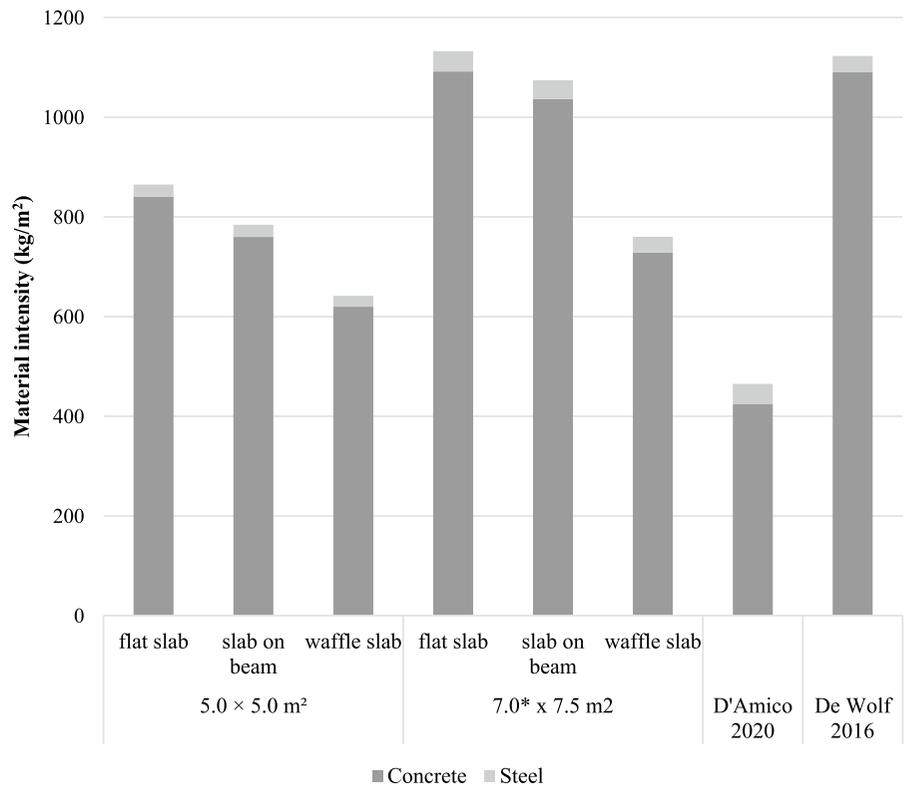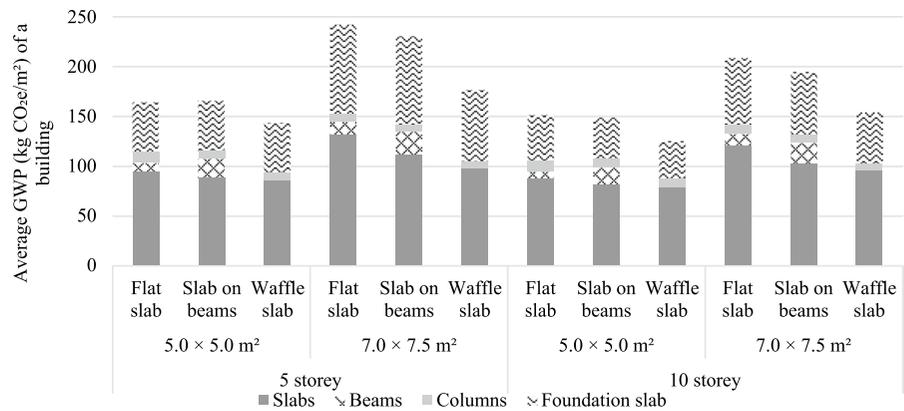
Fig. 7 Carbon footprint for 5 and 10-storey structures with varying slab systems and span widths

negative environmental impacts such as waste overflow, heat island effect and bird collision [55].

3.2 Steel reinforcement design

Design results regarding reinforcement quantities are closely correlated to the results obtained for concrete volumes, however, some differences can be observed. Differences in the design approach to adopting reinforcement (YLM, and elastic design) are negligible (between 4 and 7%), therefore in Fig. 8, only results obtained for elastic design are shown. This is due to the fact that regardless of the design approach, large parts of the slabs require minimal tensile reinforcement. Furthermore, it can be noticed with the increase in concrete class, steel quantities are also increasing for the same reason since the minimal tensile reinforcement depends on the concrete class, not the design approach, Sect. 9.2.2.1 of EC2 [39]. Also, the difference between the optimized and unoptimized

Fig. 8 Average weight of steel reinforcement for elastic design for five and ten-storey structures
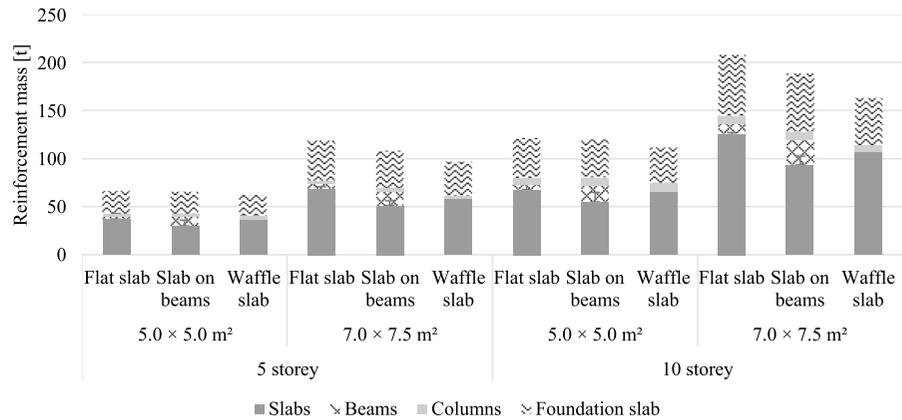
elastic design shows negligible differences in steel volume and hence in the embodied carbon. This is opposite to the emphasis previous studies gave to the role of optimized detailing of steel reinforcement as a low carbon strategy [56]. The error bars in Fig. 8 represents the differences between average quantities obtained by YLM method and the corresponding maximal/minimal average from optimized and unoptimized LEFEA.

3.3 Concrete strength

According to Purnell and Black [57], the concrete mixes designed for higher strength normally show a higher carbon footprint. However, the literature suggests that the higher the concrete strength class used in a structural element, the higher the potential to reduce the concrete volume especially of vertical members which could reduce their carbon footprint [58]. The results of the case study confirmed that, as Table 2 shows, the change in concrete class provides only minimal reduction in concrete volume in all the considered cases and accordingly the use of concrete with higher strength class results in an increase in the

carbon footprint on the building level. Also, specifying higher strength class in columns compared to horizontal members did not bring any carbon savings. The reason behind this is that regardless of the design dimensions reduction potential, the structural elements must satisfy minimal dimensions according to the code requirements as well as to allow for proper concrete casting. Previous work also concluded that the use of concrete C30/37 strength class is the optimum for low- to mid-rise buildings [59]. Out of the scope of this study, in buildings with more than 30 storeys, the significant gravity loads allow for the potential reduction of the column sizes due to the higher strength class [60].

3.4 Low-carbon concrete materials

The first material-level decarbonization strategy consists of a 30% reduction of the binder content in concrete by through the combined action of particle packing optimization and use of chemical admixtures, reduces. This strategy reduces the carbon intensity of concrete by approximately 25% regardless of the binder type. As shown in Fig. 9, the carbon footprint

Table 2 A summary of the average concrete volume and reinforcement weight in scenarios with varying strength class

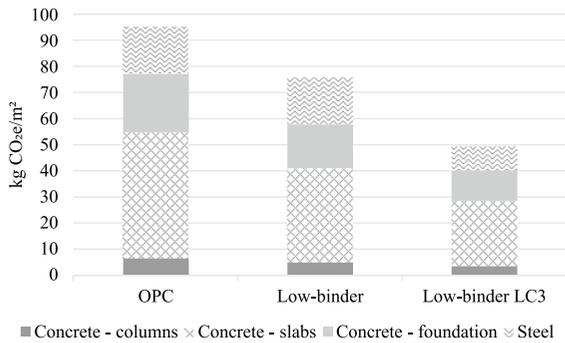| Strength class		Concrete volume (m³)			Steel weight (kg)			Average GWP total (kg CO_2e/m²)
All	Columns	Slabs	Columns	Foundation	Slabs	Columns	Foundation	
C30	C30	472	50	239	36,553	5004	20,530	148
	C50	472	38	239	36,553	3690	20,530	176
C50		472	37	239	36,071	3690	22,955	177
	C70	472	35	239	36,071	3497	22,955	205
C70		472	35	239	35,930	3497	23,890	204

Fig. 9 Building level carbon intensity of low-carbon concrete for a 10 storey 5 m span waffle slab scenario

on the building level is divided in a 70:30 ratio between concrete and steel on average. Accordingly, on the building level, the decarbonization potential of the binder reduction strategy is 20%. This value matches the conclusion from another case study by Soliman and Tagnit-Hamou [61] but is lower than the 35% reported by Long et al. [62].

The second concrete material strategy is the shift of the binder used in concrete from OPC to LC^3, which leads to a 40% reduction in the GWP of the unit mass of the binder. On a unit volume level, this translates to a 30% reduction of the concrete carbon intensity [36]. The result of this case study shows that on the building level, due to the dilution effect where a binder constitutes only 15% by mass of concrete which is responsible for only 70% of the building carbon intensity, the shift to LC^3 reduces the carbon footprint by approximately 20% on average. A reference scenario of a waffle slab system with a 5.0 m span and C30/37 concrete class was considered since it was shown to be optimum in terms of

material intensity. As shown in Fig. 8 below, the carbon intensity of the baseline alternative (Unoptimized binder content and OPC binder) on the building level is reduced from 95 to 73 kg CO_2e/m^2. The 20% reduction from the optimized binder content strategy combined with the 25% from shifting to LC3 binder results in overall 40% reduction in the building-level carbon intensity.

3.5 Summary of results and future research

The carbon footprint of the structural component of the baseline modular mid-rise building in this case study is approximately equal to the best practice reported in the literature at 250 kg CO_2e/m^2 [63] yet the seven strategies covered in this case study aimed at reducing this further. After calculating the results for the 288 alternatives, it is clear that the number of storeys (maintaining the storey height) and the use of yield line method to design the steel reinforcement do not have an influence. For the five remaining scenarios, the potential was proven to be quite significant. A shown in Fig. 10 below, for a flat slab system with a 7.5 m span, specifying a C30 concrete strength instead of C70 reduces the building level carbon intensity from 232 to 171 kg CO_2e/m^2, which is a 15% reduction. Additionally, reducing the span width to 5 m for the same flat slab system reduces it 15% more to 125 kg CO_2e/m^2. The shift of the slab system choice from a flat slab to a waffle slab could reduce the building carbon intensity 15% more to reach 95 kg CO_2e/m^2. This means that the three structural design related dematerialization strategies have a combined decarbonization potential of 60% for the selected boundary conditions and assumptions. This is 3 times the maximum quota assigned

Fig. 10 Summary of the relative decarbonization potential of all strategies included in this case study
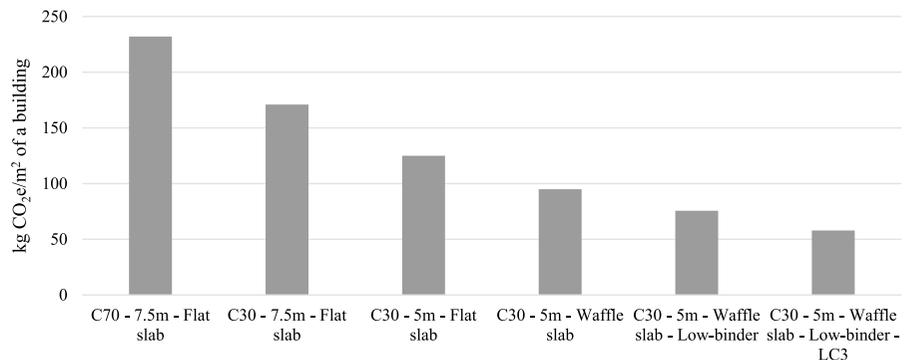
to this category of decarbonization strategy in any of the 9 global decarbonization roadmaps for cement and concrete [29]. To continue, the two strategies for low-carbon concrete studied in this case study were low-binder concrete mixes and low-carbon binders use. As shown in Fig. 10, the use of low-binder concrete could reduce the building level carbon intensity by 20%, while the use of LC^3 as a low-clinker (hence low carbon) binder in concrete could add 25% more to the total decarbonization potential. Note that the average decarbonization potential for these two strategies in global decarbonization roadmaps is only 16 and 9% respectively [29]. Hence, it is clear that currently published roadmaps underestimate significantly the decarbonization potential of commercially available and market ready decarbonization strategies [64]. This paper shows that by implementing these five strategies combined, the best practice 232 kg CO_2e/m^2 value for the carbon footprint of the structural elements of a mid-rise building could be reduced to 58 kg CO_2e/m^2only. The findings are of course limited to the assumptions of this study but still shows that 75% of the decarbonization potential of a typical urban building could be achieved through easy-to-implement commercial solutions. This conclusion aligns well with the global research efforts to explore low-hanging fruits to decarbonize the built environment within the The Global Consensus on Sustainability in the Built Environment (GLOBE) and could feed into policy documents targeting a net-zero built environment [65].

The boundary conditions selected for this case study and the potential for further research are: (1) mid-rise height with 5–10 storeys. Hence, there is room for future studies to explore the validity of the argument on high-rise buildings, (2) a raft foundation on specific soil conditions. The selection of the foundations system (pile, raft, isolated…etc.) and varying soil conditions might have led to a more optimized foundations system design and hence less decarbonization potential, but this could be a variable in future studies to understand the role of the foundations design on the carbon footprint of buildings in more details, (3) only three typical cast-in place systems while there could be further decarbonization potential in precast/prestressed slab systems such as hollowcore slabs. Finally, the inventory data used to calculate the embodied carbon of the building case studies were extracted from generic sources and hence did not account for variability in the carbon footprint of the concrete constituents regionally. This leaves room for future case-specific studies to explore material-level decarbonization strategies with primary embodied carbon data.

4 Conclusions

This paper is amongst the first to study decarbonization strategies combining material use and structural design of reinforced concrete mid-rise buildings. Following the recommendations from building stock projections, a case study of a geometrically modular mid-rise reinforced concrete building is considered. The variables investigated were the number of storeys, span width, slab system, steel reinforcement detailing, concrete mix design and finally the type of binder and steel production method. The conclusions from the 228 case study alternatives analysed can be summarized as follows:

– Irrespective of the design loads and inventory carbon data for materials, a waffle slab system saves 20–30% carbon footprint on the building level compared to slab on beams and flat slabs.
– For all three slab systems studied (flat slabs, slab on beams and waffle slabs), reducing the span of the slab from 7.5 to 5.0 m saves 20–30% more of the building embodied carbon.
– The increase in the number of storeys from 5 to 10 (while maintaining a constant storey height) does not necessarily increase the carbon footprint of the building.
– For a mid-rise building and up to 7.5 m spans, the use of C30/35 class concrete strength is optimum for the load combinations considered. The increase of the strength of the columns specifically or the whole building will only increase the building's embodied carbon.
– Other decarbonization strategies suggested by the literature such using the yield line method for reinforcement design or optimizing the reinforcement detailing for the structural members were shown to be ineffective in the studied cases.
– The use of concrete with 30% less binder content and 50% less clinker could save further 45% in terms of the CO_2 impact per built-up area.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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