

1 14/01/2022

2 Word count - 7182

3 **Comparing different strategies of minimising embodied carbon**
4 **in concrete floors**

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Abstract

The present climate emergency demands the construction industry to minimise the carbon footprint of concrete buildings. In this paper, the potential different optimisation strategies to reduce ‘cradle-to-gate’ embodied carbon of concrete floors which require different levels of modifications to the conventional design and construction practice were compared. The embodied carbon savings possible from parametrically optimising slab depth and grade of concrete, post-tensioning, considering alternative conventional slab types, and adopting novel thin shell floor systems were quantified for a range of spans. Compared to reinforced concrete flat slabs designed for conventional span/depth ratios, minimising slab depths and considering lower grades of concrete can reduce embodied carbon of flat slabs up to 12%, only with changes to the design methods. By adopting other conventional alternatives available in the present market, post-tensioning can save embodied carbon up to 23% but two-way slabs on beams and hollow-core slabs can save up to 36%. Much higher carbon reductions up to 65% are possible with novel construction methods of thin shell floors that transfer loads through membrane action rather than bending. Hence, the construction industry should approach shape optimised floor construction forms in future while adopting parametric design and considering conventional alternatives in the present to minimise carbon emissions.

Keywords: concrete floors; embodied carbon; parametric design; optimisation strategies; alternative construction forms

47 **1 Introduction**

48 The construction industry is responsible for a rising share of carbon emissions. The
49 greenhouse gas emissions from global cement production alone are 6% of the total
50 emissions due to human activities (UNFCCC, 2017). Hence, minimising the carbon
51 footprint of buildings is of utmost importance in the present context. As the quantity of
52 greenhouse gas emitted due to the construction activities, embodied carbon can be
53 used to quantify the environmental impact of building designs. Sansom and Pope
54 (2012) and Foraboschi et al. (2014) showed that up to 75% of the embodied carbon of
55 the superstructure is from floors. Different researchers have demonstrated various
56 strategies to minimise embodied carbon of concrete floors which require some changes
57 to the conventional methods in design, and construction. Eleftheriadis *et al.* (2018),
58 Trinh *et al.* (2021) and Ferreiro-Cabello *et al.* (2016) developed optimisation algorithms
59 to minimise embodied carbon of concrete flat slabs by varying different design
60 parameters, and their findings are applicable without changing the present construction
61 methods of reinforced concrete flat slabs. Kaethner and Burridge (2012), Drewniok
62 (2021) and Goodchild *et al.* (2009) compared different systems available in the market
63 to identify the floor type with minimum embodied carbon for given design criteria, where
64 implementing the findings need changes in the early stage procurement. Block *et al.*
65 (2017) and Hawkins *et al.* (2020) developed novel low carbon floor systems to remove
66 unwanted concrete by transferring loads through compressive membrane actions
67 rather than flexure. Implementing such optimisation techniques may require different
68 levels of effort, based on the local market technology maturity and availability of
69 options. As an example, adopting a novel shape optimised floor system may require
70 more investments and training, compared to a method of optimising the floor designs
71 with available construction practice. Also, different optimisation techniques may result
72 in different levels of carbon savings. Therefore, this study compares and contrasts

73 different strategies to reduce embodied carbon of concrete floors which require
74 different levels of modifications to the conventional design and construction practice.

75 **2 Literature Review**

76 Embodied carbon has been widely used as a performance indicator in optimising the
77 environmental impacts of buildings. Carbon emissions associated with extraction and
78 manufacturing of building materials and products, transportation, maintenance, and
79 disposal can be identified as embodied carbon (Hammond and Jones, 2008; RICS,
80 2017; Gibbons and Orr, 2020). BS EN 15978 (BSI, 2011) standardises the assessment
81 of buildings by defining different stages of the lifecycle. The stages A1 to A3 represent
82 the emissions related to raw material extraction, transportation, and manufacturing in
83 the 'Product' stage, defined as 'cradle-to-gate'. The case studies by Monahan and
84 Powell (2011), Nadoushani and Akbarnezhad (2015), Meneghelli (2018), Li *et al.*
85 (2013), Moncaster *et al.* (2018) illustrated that 'cradle-to-gate' phase is responsible for
86 around 70% to 90% of total life cycle embodied carbon. The databases such as
87 Inventory of Carbon and Energy (Circular Ecology, 2021) presents 'cradle-to-gate'
88 embodied carbon coefficients for various building materials. Total embodied carbon of
89 buildings can be estimated based on such databases as the performance indicator for
90 structural optimisation.

91 Despite the present climate emergency, the construction industry is resistant to novel
92 low carbon techniques. Gieseke *et al.* (2016) surveyed the barriers to the uptake of
93 low carbon building materials and identified a range of issues in terms of institutional,
94 habitual, economic, technical, knowledge, and perception. Orr *et al.* (2019) also
95 implemented a survey and highlighted that ease of construction is valued more than
96 material efficiency and emphasised aligning incentives to minimise carbon emissions.
97 Kershaw and Simm (2014) surveyed the drivers and obstacles to low carbon design of

98 school buildings and revealed the complexity of building systems and perceived extra
99 cost as common barriers. Pan and Pan (2021) also surveyed the industry partners and
100 identified that the challenges to implementing low carbon methods can be economical,
101 legislative, cultural, knowledge and even geographical. Hence, understanding the
102 potential savings of embodied carbon by different optimisation strategies against the
103 required modifications to the conventional design and construction practice is useful in
104 decision making.

105 Flat slab solutions are popular in the construction industry due to presumed speed and
106 ease of construction, minimum overall depth, flat soffit, absence of beams, and
107 flexibility in the plan layout (British Cement Association, 2001; The Concrete Society,
108 2007). The conventional design process of flat slabs may begin with a predetermined
109 span/depth ratio on a determined column grid, following guidelines such as by IStructE
110 (IStructE, 2017) or The Concrete Centre (Bond *et al.*, 2019). Different researchers have
111 approached the optimisation of flat slabs in different scopes and methods. Trinh *et al.*
112 (2021) parametrically optimised flat slab designs and illustrated that the lowest carbon
113 designs were associated with shorter spans, thinner slab depths, and lower grades of
114 concrete. They also demonstrated that carbon reductions up to 33% were possible by
115 post-tensioning. Miller *et al.* (2015) further supported their claims by designing flat
116 slabs for a range of spans and reducing embodied impacts up to 40% by post-
117 tensioning. Ferreiro-Cabello *et al.* (2016) designed a range of flat slabs for three
118 different column grids and highlighted the importance of minimising column spacing
119 while demonstrating the nonlinear behaviour between slab thickness and embodied
120 carbon. Nevertheless, they obtained minimum embodied carbon with designs closer to
121 minimum allowable slab thickness but showed a possibility of having optimum in a
122 marginally deeper slab for more than 6 m spans. Eleftheriadis *et al.* (2018) also
123 optimised flat slabs with a BIM-based genetic algorithm varying column layout, member

124 sizes and reinforcing details, and claimed that the layout has the largest impact on
125 embodied carbon. They also discussed the possibility of minimising embodied carbon
126 by increasing slab thickness, but such examples had carbon savings around 1%.
127 Therefore, embodied carbon of flat slabs can be reduced by optimising the column
128 layout, slab thickness, reinforcing details, grade of concrete, and by post-tensioning,
129 where the required design modifications are applicable within the available construction
130 practice.

131 Several studies have investigated the difference in embodied carbon of conventional
132 floor systems. Kaethner and Burrige (2012) compared flat slabs, post-tensioned flat
133 slabs, and several types of precast and composite slabs for three building designs, and
134 concluded no structural scheme gave the lowest embodied carbon consistently.
135 Goodchild *et al.* (2009) developed design guidelines based on parametric analysis for
136 economic frames with one-way slabs, one-way slabs with wide beams, ribbed slabs,
137 troughed slabs, two-way slabs on beams, flat slabs, waffle slabs, post-tensioned flat
138 slabs, and hollow-core slabs. They recommended which slab type would be
139 economical for which spans but haven't compared the cost or embodied carbon
140 despite recommending several slab types for some spans. Referring to their design
141 charts, Drewniok (2021) compared the variation of the embodied carbon of flat slabs,
142 post-tensioned flat slabs, two-way spanning slabs on beams, waffle slabs, hollow-core
143 slabs, and composite hollow-core slabs with column spacing. They observed that
144 waffle slabs had minimum embodied carbon for all the spans considered. From the
145 other slab forms, the lowest embodied carbon was with composite hollow-core slabs for
146 spans longer than 7 m and flat slabs or two-way spanning slabs on beams for shorter
147 spans. Based on Goodchild *et al.* (2009)'s work, The Concrete Centre (2020)
148 developed the programme 'Concept V4' to compare cost and embodied carbon of
149 different slab types for an input column grid. Therefore, considering alternative slab

150 types available in the construction market at the preliminary design stage is proven to
151 be important in minimising embodied carbon in buildings.

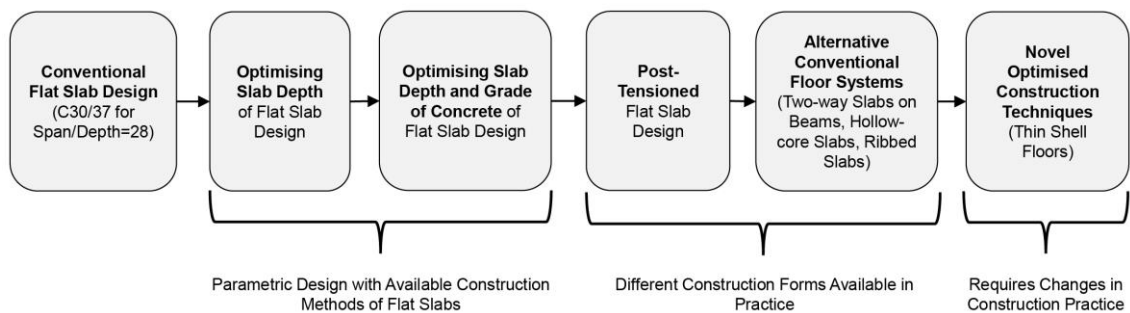
152 Concrete floor systems in which the load transferring mechanism is based on flexure
153 essentially keep concrete mass under the neutral axis in tension, ignore in design and
154 not fully utilising the capacity. Hence, concrete floors with flexural load paths are often
155 wasteful, despite their popularity. Several research groups are exploring the possibility
156 of reducing the amount of concrete required for floors by switching the dominant
157 structural behaviour from bending to membrane action. Block *et al.* (2017) described
158 how vaulted concrete shells stiffened with ribs can reduce embodied carbon in floors.
159 Liew *et al.* (2017) and Rippmann *et al.* (2018) proceeded to develop necessary
160 prototypes using tailored formwork and additive manufacturing respectively. Hawkins *et*
161 *al.* (2019, 2020) also illustrated how embodied carbon can be reduced in concrete
162 floors with textile reinforced thin concrete shells and prestressed steel ties. Such novel
163 construction forms are still being further researched and would require further
164 investments for the uptake in the industry irrespective of possible attractive carbon
165 reductions. However, it is important to consider such cutting-edge floor types as a
166 viable strategy to minimise embodied carbon in concrete floors by adopting novel
167 construction techniques.

168

169 **3 Methodology**

170 This study compares the effectiveness of different carbon reduction strategies for
171 concrete floors depending on the effort required to adopt them (Figure 1). Starting from
172 the conventional design of reinforced concrete flat slab, stepwise changes to traditional
173 design and construction practice are introduced to minimise embodied carbon, as
174 follows.

- 175 1. Optimise flat slabs by only changing the design approach (requires no change
 176 in the present construction practice of flat slabs)
 177 a. Parametric design to optimise slab depth
 178 b. Parametric design to optimise slab depth and grade of concrete
 179 2. Consider alternative floor systems in practice (requires selecting other
 180 conventional slab types available in the market)
 181 a. Post-tensioned flat slabs
 182 b. Other conventional alternatives such as two-way slabs on beams,
 183 hollow-core slabs, and ribbed slabs
 184 3. Adopt novel construction methods based on shell floors (requires changes in
 185 the present construction practice)



188
189 **Figure 1: The strategies to minimise embodied carbon in concrete floors in the order of**
 190 **effort required to implement them**

191
192 Discrete floor designs were generated to represent the above five approaches
 193 considering a layout of 3 bay x 3 bay square column grids. The column spacing was
 194 parametrically varied from 4 m to 12 m in 1 m intervals to generate sufficient data

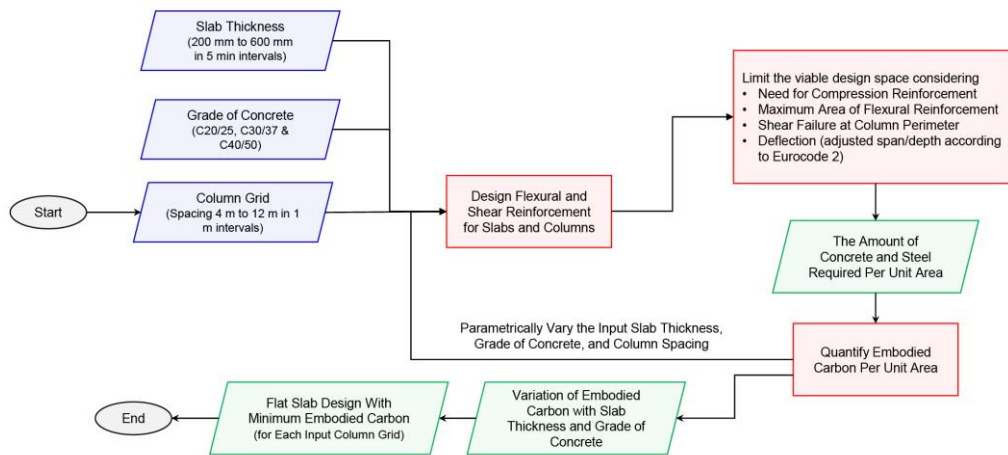
195 points to observe its impact on each carbon optimisation strategy. The design of floors
196 in office buildings was idealised in this study with a superimposed dead load of 1.5
197 kN/m², an imposed load of 2.5 kN/m², and a perimeter load of 10 kN/m for cladding.
198 Only the structural frame of one storey floor was considered in this scope for embodied
199 carbon calculations. The quantity of construction materials required for slabs, beams,
200 columns, and shells for each design was estimated to calculate the embodied carbon
201 per unit floor area.

202 **3.1 Parametric Optimisation of Flat Slabs**

203 The flat slab design with minimum embodied carbon for a given column grid was
204 identified by developing a series of designs parametrically varying the slab depth, and
205 grade of concrete, as explained in Figure 2. The flat slabs were designed based on BS
206 EN 1992-1-1 (BSI, 2015), and the relevant supporting guidelines (The Concrete
207 Society, 2007; The Concrete Centre, 2009; Bond *et al.*, 2019). A MATLAB program
208 was developed to design the flat slabs and estimate the embodied carbon due to their
209 repetitive nature. The design moments were calculated considering slab strips as
210 beams spanning between column and middle strips. The amount of reinforcement was
211 treated as a continuous variable. When the column spacing, slab depth, and the grade
212 of concrete is input, the developed MATLAB programme calculated the required
213 amount of flexural and shear reinforcement. The flexural reinforcement was calculated
214 for top and bottom layers for both directions considering moments at column points and
215 spans in the column strips and middle strips. The reinforcement along the grid lines on
216 the edges of the plan area and in the middle were also separately designed. A moment
217 redistribution of 15% was adopted. The detailing requirements at columns and
218 simplified curtailment rules were also considered referring to the guides by The Concrete
219 Centre (The Concrete Society, 2007; Bond *et al.*, 2019). The punching shear links were
220 designed considering square-shaped columns at the corner, side, and internal points.

221 Since the column spacing has a direct impact on optimisation, columns were also
 222 designed with C30/37 at the corner, side, and internal positions. The column size was
 223 taken as 6% of the span to keep the design stress less than 17 N/mm², referring to
 224 preliminary design tables in IStructE (2017) guidelines. To achieve realistic results, the
 225 design load for columns were based on the load of three storeys, and the column
 226 height was taken as 3.5 m. The amount of reinforcement in the columns was calculated
 227 referring to the design charts by The Concrete Centre (Bond *et al.*, 2019). Thereafter,
 228 the programme quantified the amount of concrete and steel per unit area for each
 229 design considering both slabs and columns to estimate embodied carbon per unit area.
 230 The extent of the design space of flat slabs was limited by the following factors.

- 231 • Need of compression reinforcement
- 232 • Maximum area of flexural reinforcement (4%)
- 233 • Shear failure at column perimeter
- 234 • Deflection- based on adjusted span/depth ratio according to BS EN 1992-1-1



235

236 **Figure 2: Method of Parametric Optimisation of Flat Slabs**

237

238 The minimum slab thickness was limited to 200 mm considering a fire rating of R90.
239 The nominal cover to reinforcement was taken as 25 mm considering 15 mm minimum
240 for concrete inside buildings with low air humidity, and an additional 10 mm for
241 deviations. The effective depths were calculated assuming a reinforcement bar
242 diameter of 20 mm. Vibration performance was not considered in this scope since the
243 concrete floors generally meet vibration criteria due to inherent mass (Brooker, 2009).
244 Durability concerns require the use of C30/37 or higher grades use in office buildings
245 for both indoor and outdoor environments according to BS EN 1992-1-1, but C20/25
246 was also considered in this study to explore the potential of reducing embodied carbon.

247 For a given column spacing, flat slabs were designed for thicknesses varying from 200
248 mm to 600 mm in 5 mm intervals, using C20/25, C30/37, and C40/50. Comparing the
249 embodied carbon of each design could identify the flat slab design with minimum
250 possible embodied carbon for the selected column spacing. Likewise, optimum floor
251 designs with reinforced concrete flat slabs for spans varying from 4 m to 12 m were
252 identified.

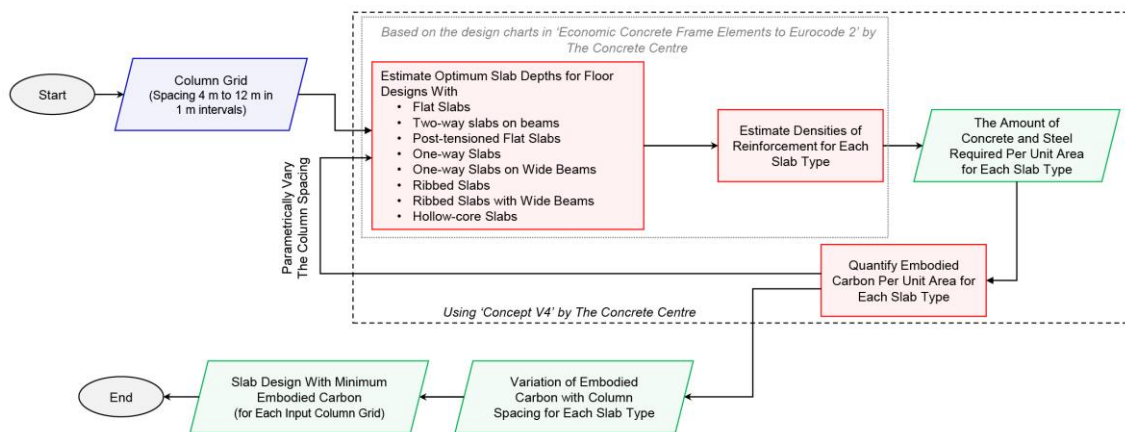
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254 **3.2 Alternative Concrete Slab Systems**

255 The program 'Concept V4' (The Concrete Centre, 2020) developed by the concrete
256 centre was used in this study to generate floor designs for eight alternative slab
257 systems, as described in Figure 3. The programme is based on the guide 'Economic
258 Concrete Frames to Eurocode 2' (Goodchild, Webster and Elliott, 2009) by The
259 Concrete Centre. The guide contains design charts to select the slab thickness for
260 several conventional slab types for a range of column spacing and imposed loads. The
261 estimated reinforcement densities are also parallelly listed. The design charts have
262 been developed based on a series of parametric designs to minimise the cost.

263 'Concept V4' uses those design charts to estimate the required material quantities and
 264 then the embodied carbon per unit area for each design. The above guide has charts
 265 for optimised beam designs as well, and 'Concept V4' uses them to design the beams
 266 wherever necessary (e.g.: for two-way spanning slabs on beam and hollow-core slabs).
 267 The embodied carbon estimations of floor designs with flat slabs, two-way slabs on
 268 beams, post-tensioned flat slabs, one-way slabs, one-way slabs on wide beams, ribbed
 269 slabs, ribbed slabs with wide beams, and hollow-core slabs were obtained for each
 270 column spacing. The floors were designed with C30/37 except for post-tensioned flat
 271 slabs which used C32/40. The embodied carbon coefficients in the program were
 272 amended based on the literature review in this study, as explained in Section 3.4. The
 273 program was refined to quantify the embodied carbon of the structural frame of one
 274 storey only, excluding the common allowances such as ground floor slabs.

275



276

277 **Figure 3: Method of Alternative Analysis for Concrete Slabs**

278

279 'Concept V4' is capable of comparing both the embodied carbon and the cost of
 280 different floor solutions for an input column grid. In the scope of this paper, only the

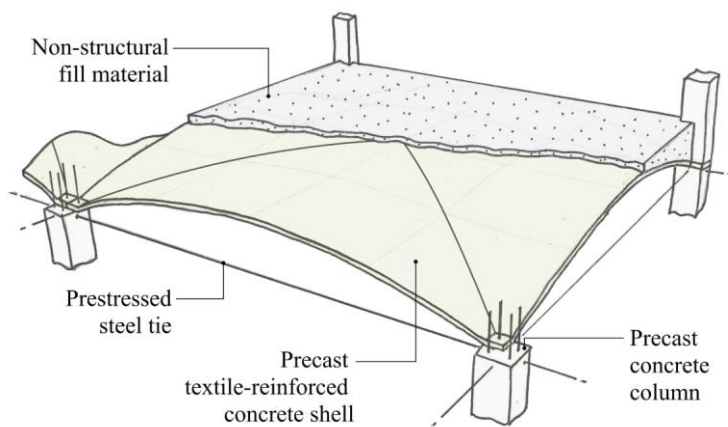
281 embodied carbon is discussed, whereas the authors (Jayasinghe *et al.*, 2021) have
282 comprehensively discussed the cost vs embodied carbon of conventional slab types in
283 a separate article.

284

285 **3.3 Novel Optimised Construction Techniques**

286 The floor system proposed by Hawkins *et al.* (Hawkins, 2019, 2020; Hawkins *et al.*,
287 2019, 2020) based on thin textile-reinforced concrete shells and prestressed ties were
288 considered (Figure 4) as an example of a less conventional but also less carbon-
289 intensive alternative floor system. The uniform thickness shells were supposed to be
290 cast with fine-grained concrete and reinforced with two layers of glass fibre textile. The
291 shells were designed as groin vaults to primarily act in compression, while steel ties
292 were designed to act in tension. The top surfaces of the floors were filled with a
293 recycled aggregate fill to create a flat surface. Since the design tables did not contain
294 the data for column design, the relevant shares of embodied carbon from columns
295 were extracted from the flat slab analysis. The design charts (Hawkins, 2020) referred
296 to in this study provide shell thickness, steel tie diameter, overall height, column width,
297 fibre reinforcement ratio, and grade of concrete for the design with minimum embodied
298 carbon for a given span.

299



300

301 **Figure 4: Thin Shell Floor System with Textile Reinforced Concrete and Prestressed Steel**
 302 **Ties**

303 **3.4 Estimating Embodied Carbon**

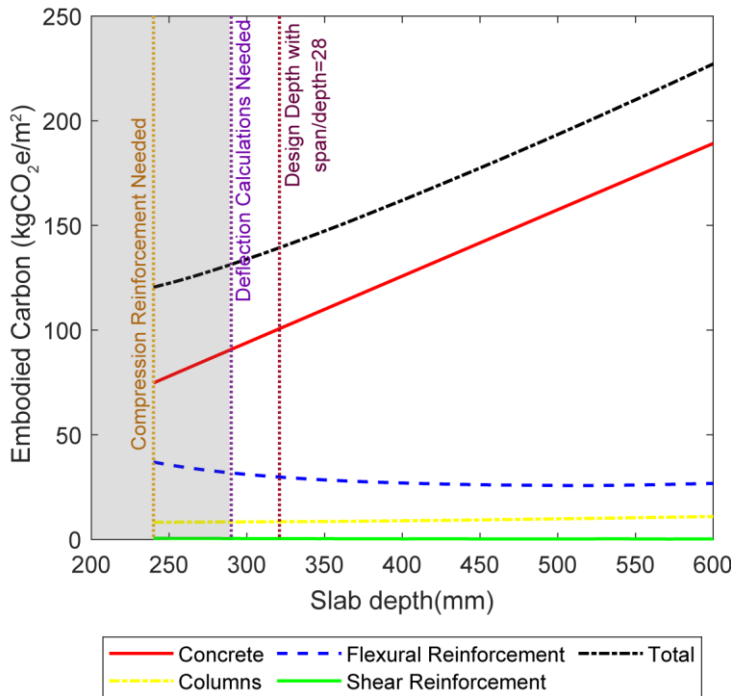
304 The embodied carbon of all the generated designs was calculated for the lifecycle
 305 phases from A1 to A3 according to BS EN 15978 (BSI, 2011), defined as 'cradle-to-
 306 gate'. Only the materials in slabs, beams, columns, and shells with fillers for one storey
 307 are considered in the estimation of embodied carbon. The effects outside the
 308 boundaries and one-storey structural frames such as formwork, construction process,
 309 foundations and common allowances were excluded in this scope. The carbon
 310 coefficients given in The Inventory of Carbon and Energy by Circular Ecology (2021)
 311 were adopted wherever available. The coefficients for concrete were based on average
 312 blends of cement. Since the thin shell floor designs for different spans recommended
 313 different grades of concrete, a consistent relationship between the grade of concrete
 314 and the embodied carbon was needed in this scope. Hence, the carbon coefficients for
 315 grades absent in the database were extrapolated based on the available data and
 316 Feret's law which states that the concrete strength is proportional to the square root of
 317 the cement content (de Brito, Kurda and da Silva, 2018). The fine-grained concrete
 318 used in the shell floors may be less dense and high carbon than the values assumed,

319 depending on aggregate gradation and workmanship, hence not considered in this
320 study. The carbon coefficient for glass fibre textile was based on a literature review in a
321 previous study (Hawkins, 2019). The coefficients for hollow-core panels were extracted
322 from recommended values in 'Concept V4' which had been obtained from environment
323 product declarations and recalculations. The embodied carbon coefficients for steel
324 reinforcement and post-tensioning tendons were considered the same in this scope.
325 The densities of concrete, steel, glass fibre textile, and aggregate fill were taken as
326 2400 kg/m^3 , 7850 kg/m^3 , 2700 kg/m^3 , and 1400 kg/m^3 respectively. The carbon
327 coefficients used in this study are presented in Table A1 in Appendix. Embodied
328 carbon per unit floor area was calculated for each design for comparison.

329 **4 Results and Discussion**

330 Figure 5 presents the results of parametric optimisation of flat slabs with C30/37 for 9
331 m column spacing. As a rule of thumb conventional benchmark, a flat slab design with
332 a span/depth of 28 referring to the guidelines by Brooker (2009) is also marked in the
333 same plot. The shaded area represents the unfeasible designs. The feasible space has
334 been limited by limiting span/depth ratio for deflection in this case, instead of either fire
335 criterion or the need of compression reinforcement. Even though the contribution of
336 embodied carbon from steel decreases when the design slab depth is increased, the
337 subsequent share from concrete is increased at a higher rate. Also, at least 2/3 of the
338 total embodied carbon of the slabs in this scope was from concrete. Therefore, design
339 with minimum embodied carbon approached the minimum allowable slab thickness.
340 The contribution from the shear reinforcement to total embodied carbon was negligible.
341 Also, the embodied carbon share from columns was low compared to the other
342 elements and had insignificant variation throughout the range of column spacings
343 considered.

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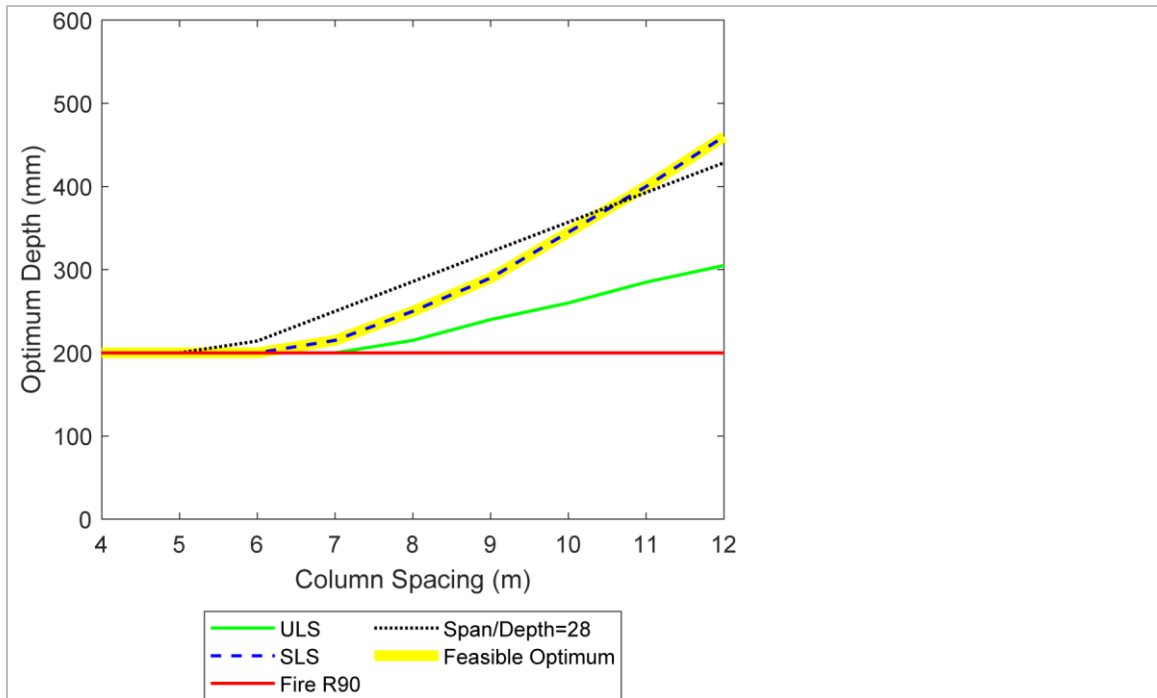
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346 **Figure 5: Parametric Design of Flat Slabs for 9 m Span with C30/37**

347

348 Expanding the scope of Figure 5 for a range of column spacings, Figure 6 shows the
349 optimum depths identified in the parametric design of flat slabs with C30/37. Optimum
350 depths coincided with the minimum possible depth in all the spans considered in this
351 scope, leaving no room for trade-offs between slab depth and amount of reinforcement.
352 The optimum depth of flat slabs for spans less than 6 m were governed by fire criterion,
353 whereas deflection criterion governed the designs with longer spans. The selected
354 conventional span/depth ratio of 28 did not satisfy the deflection criteria for spans
355 longer than 11 m. Still, the parametric design could reduce slab by up to 35 mm from
356 the conventional design depths, saving up to 8% of embodied carbon.

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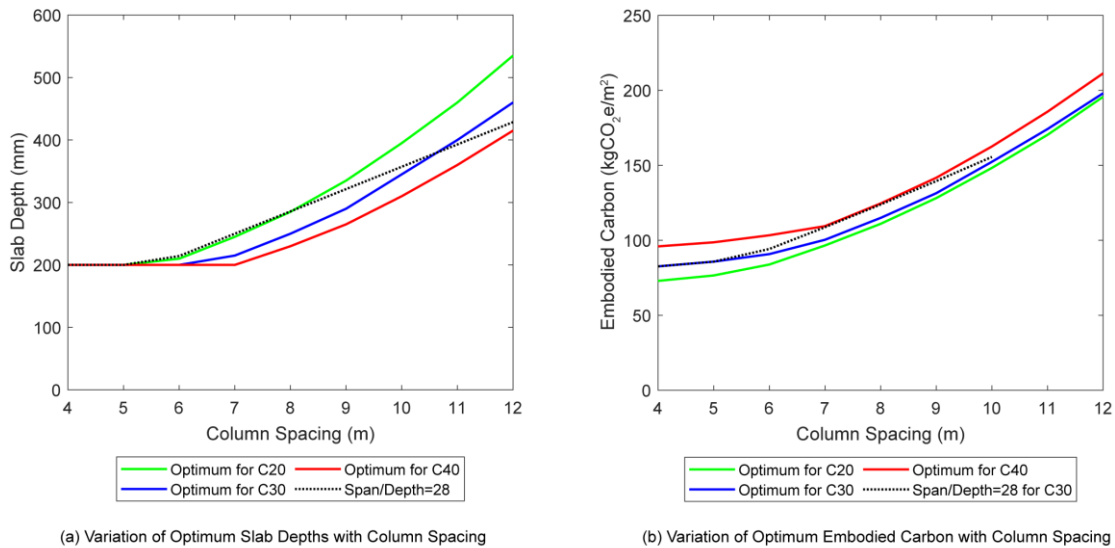
359 **Figure 6: Variation of Optimum Depth and Governing Criteria with Column Spacing for**
 360 **Flat Slabs with C30/37**

361

362 Repeating the methods used for Figure 6, Figure 7 reports the variation of optimum
 363 slab depth and the embodied carbon with column spacing for three different grades of
 364 concrete. Using C40/50 instead of the conventional selection of C30/37 could reduce
 365 the optimum slab depths of flat slabs with spans longer than 6 m, but embodied carbon
 366 increased for all the spans. Lowering the grade of concrete to C20/25 increased the
 367 optimum slab depths but reduced the overall embodied carbon in all the spans
 368 considered. The embodied carbon curves kept decreasing for lower spans even if the
 369 slab depths remained at the same minimum allowable because of the less
 370 reinforcement needed. The savings of embodied carbon possible from lowering the
 371 grade of concrete compared to parametrically optimised flat slabs with C30/37 were up
 372 to 11%, but the savings for spans longer than around 7m was marginal. Using C20/25

373 for office buildings may require further research in terms of durability concerns, but only
374 the aspect of embodied carbon is included in this scope.

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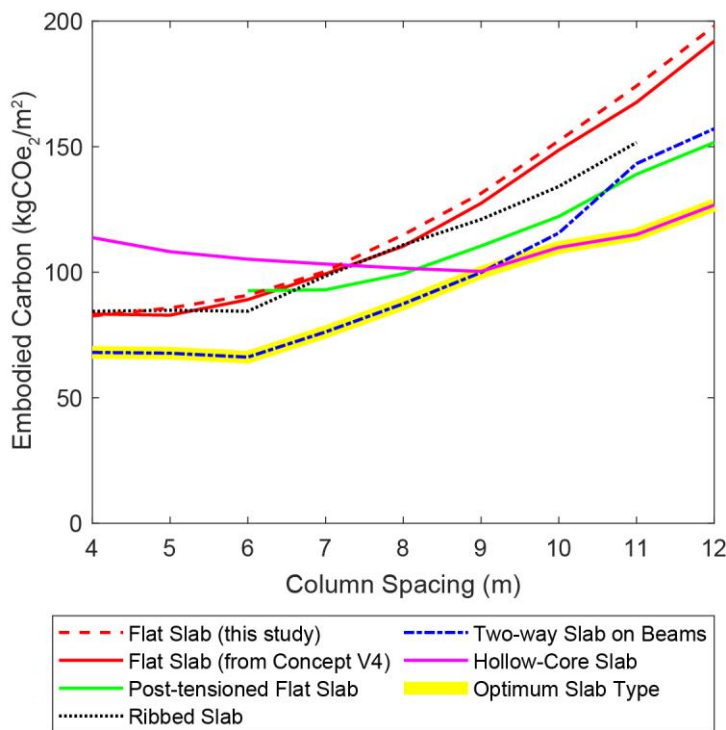
377 **Figure 7: Variation of the Optimum Slab Depth and the Corresponding Minimum Possible**
378 **Embodied Carbon with Column Spacing for Flat Slabs with Different Grades of**
379 **Concrete**

380

381 The outcome of considering alternative conventional slab types is presented in Figure
382 8. To provide some degree of verification, the results for optimised flat slab designs
383 from both Concept V4 and the parametric optimisation in this study are presented
384 together in Figure 8. Both the curves followed a similar pattern, having a difference
385 under 4% throughout. The variation of embodied carbon with column spacing only for
386 flat slabs, post-tensioned flat slabs, two-way slabs on beams, hollow-core slabs, and
387 ribbed slabs are plotted to avoid congestion. The other slab types considered in the
388 programme did not result in designs with the lowest embodied carbon for any of the
389 spans considered. The different slab types considered in this scope had different

390 optimum column spacings, 9 m for hollow-core slabs and within 5 m to 7 m for others.
 391 Post-tensioning reduced embodied carbon in the flat slabs with spans longer than 7 m,
 392 and the savings increased with the span. However, the slab type with the least
 393 embodied carbon changed with the column spacing. The optimum slab system was
 394 two-way spanning slabs on beams for spans shorter than 9 m, and hollow-core slabs
 395 for longer spans. Hence, considering two-way slabs on beams and hollow-core slabs
 396 instead of flat slabs could reduce embodied carbon by 18% to 33%.

397



398

399 **Figure 8: Variation of Embodied Carbon with Column Spacing for Different Alternative**
 400 **Conventional Floor Systems**

401

402 Table 1 contains the design details of the optimised floor at each step. Conventional
 403 flat slabs were designed with C30/37 based on the span/depth ratio of 28. Since the

404 span/depth ratio of 28 was not sufficient for spans longer than 11 m, the conventional
 405 flat slab designs for those spans were considered to be the same as the parametrically
 406 optimised designs with C30/37. The slab thicknesses optimised for C30/37 and C20/25
 407 are subsequently reported. The solutions with post-tensioned flat slabs and other
 408 alternatives are directly extracted from the output of Concept V4. The thickness and
 409 the grade of concrete for the thin shell floor system are presented whereas the vault
 410 rise is fixed to be 10% of the span.

411

412 **Table 1: Optimum Floor Designs at Each Optimisation Step**

Span (m)	Conventional FS	Optimum FS	Optimum FS with C20	PT FS	Alternative Slab Type	Thin Shell Floors
4	200 mm	200 mm	200 mm		TW 125 mm (250 mm)	32 mm C40 (400 mm)
5	200 mm	200 mm	200 mm		TW 125 mm (250 mm)	
6	214 mm	200 mm	205 mm		TW 125 mm (275 mm)	43 mm C45 (600 mm)
7	250 mm	215 mm	245 mm	200 mm	TW 141 mm (350 mm)	
8	286 mm	250 mm	285 mm	215 mm	TW 166 mm (450 mm)	61 mm C45 (800 mm)
9	321 mm	290 mm	335 mm	240 mm	TW 191 mm (575 mm)	
10	357 mm	345 mm	395 mm	275 mm	HC 250 mm (750 mm)	83 mm C45 (1000 mm)
11	400 mm	400 mm	460 mm	310 mm	HC 250 mm (750 mm)	
12	460 mm	460 mm	535 mm	340 mm	HC 300 mm (900 mm)	93 mm C50 (1200 mm)
FS- Flat Slab; PT- Post-tensioned; TW- Two-way slabs on beams; HC- Hollow-Core Slabs; (<i>Total Structural Depth</i>)						

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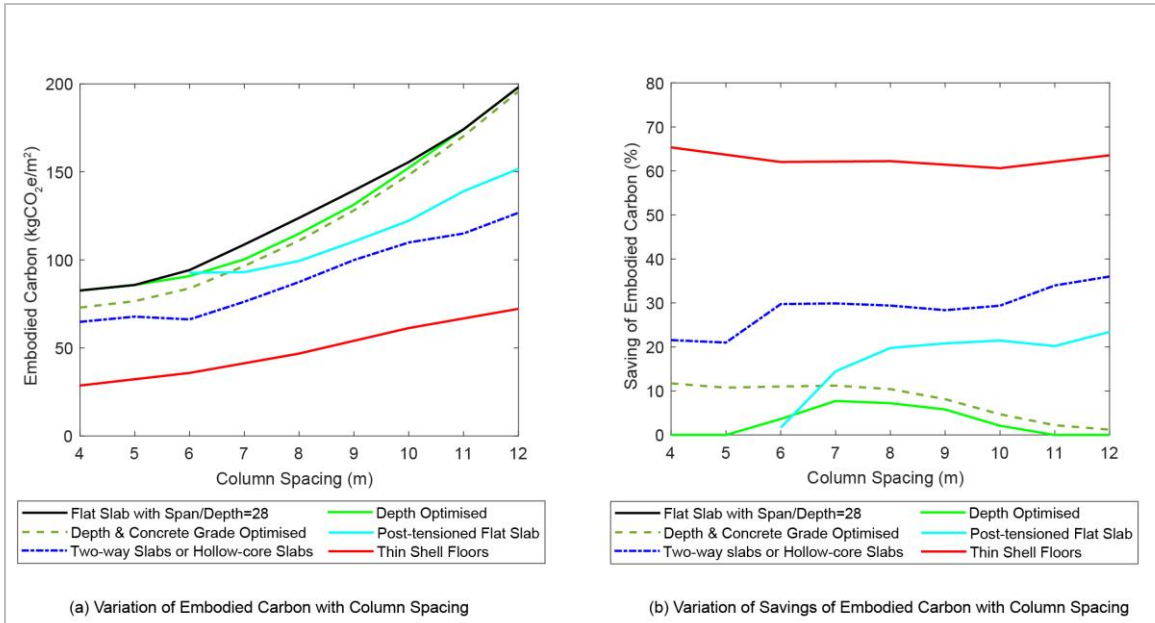
414 Based on the designs in Table 1, Figure 9 describes the variation of optimum
 415 embodied carbon and possible savings of each optimisation strategy with column
 416 spacing. Compared to the conventional design of flat slabs with C30/37, embodied

417 carbon can be reduced by 2% to 8% by optimising design depth for column spacings
418 between 6 m and 10 m. Parametric design of flat slabs varying both design depth and
419 grade of concrete can reduce embodied carbon up to 12% from traditional designs.
420 Optimising the design of flat slabs for a given span converged to minimising slab
421 thickness and adopting lower grades of concrete in this scope where office buildings
422 were considered. Such changes in the design process can be easily facilitated with
423 professional training, without changes in the construction methods. Post-tensioning the
424 flat slabs result in a decrease in embodied carbon by 14% to 23% for spans longer
425 than 7 m. Carbon savings of about 21% to 36% can be achieved by considering two-
426 way slabs on beams and hollow-core slabs as conventional alternatives. The technical
427 knowledge and the required resources are available in the present market for these
428 conventional alternatives. Moving towards novel floor systems that transfer loads
429 through membrane actions rather than flexure to reduce concrete consumption such as
430 thin shell floors can achieve significant carbon savings up to 65%. In all the
431 optimisation strategies considered, embodied carbon generally increased with the
432 column spacing, highlighting the importance of minimising the spans.

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436

437

Figure 9: Variation of Optimum Embodied Carbon and Possible Carbon Savings with Column Spacing for Different Optimisation Approaches

438

439

440

The outcomes of each optimisation strategy considered in this study aligned well with

441

the other studies referred to in the literature review. The design charts developed by

442

Goodchild, Webster and Elliott (2009) provide thicknesses with the optimum cost for

443

flat slabs with C30/37 for a range of spans. The flat slab designs parametrically

444

optimised in this study using C30/37 closely followed the embodied carbon values

445

given by Concept V4 which used the above guide. Both Ferreiro-Cabello *et al.* (2016)

446

and Trinh *et al.* (2021) also had proved that minimising slab thickness and adopting

447

lower grades of concrete can reduce embodied carbon of reinforced concrete flat

448

slabs. The aspects which were not discussed in this article such as reinforcement

449

detailing, deflection control, and the adopted carbon coefficients can have an impact on

450

the optimisation of flat slab designs. The authors plan to discuss parametric

451

optimisation of flat slabs further in a separate article. The list of conventional slab

452

alternatives considered in this study has some differences from those of similar

453 previous studies by Kaethner and Burridge (2012) and Drewniok (2021). Still, all three
454 studies commonly agreed that the slab type with the minimum embodied carbon will
455 depend on the column grid. The state-of-the-art floor systems discussed in this study
456 are based on removing unwanted concrete by switching from slab systems that are
457 based on bending to vault systems that predominantly act as compressive membranes.
458 Even though the potential savings of embodied carbon are promising, further research
459 is needed in terms of vibration, acoustics, fire safety and lateral stability (Hawkins *et al.*,
460 2020). Thus, this study applied different optimisation strategies which have different
461 levels of maturity in the literature for the same set of building designs to compare the
462 potential carbon savings.

463 Despite the rising environmental concerns, the construction industry resists adopting
464 low carbon methods due to various concerns regarding knowledge, perception, and
465 economy. Therefore, understanding the possible carbon savings from different
466 optimisation strategies which need different levels of effort in implementation is crucial
467 in the present context. This study compared five strategies to reduce embodied carbon
468 in concrete floors that require different levels of modifications to the conventional
469 design and construction practice. Each strategy was implemented in a typical office
470 building design for a range of column spacings to compare their potential of reducing
471 embodied carbon and to understand how the effectiveness of each strategy varies with
472 span. Parametrically developing a series of designs and scanning through the feasible
473 solutions can reduce embodied carbon of reinforced concrete flat slabs up to 8% from
474 conventional designs. If the same optimisation algorithm is applied to designs with
475 C20/25, the savings can be up to 12%. These carbon savings can be achieved by
476 changing only the design approach of flat slabs, without changing the construction
477 methods currently used in the industry. Post-tensioning requires some modifications to
478 the construction procedure of reinforced concrete flat slabs, but the potential reductions

479 of embodied carbon can be even up to 23%. Switching from flat slabs to other slab
480 types such as two-way slabs on beams or hollow-core slabs needs changes to the
481 method of construction, but the industry has the matured knowledge of such
482 alternatives. Considering available alternatives can decrease embodied carbon of
483 concrete floors by up to 36% compared to conventional flat slab designs. The novel
484 shape optimised floor systems can cut down embodied carbon up to 65% but need to
485 be further researched and invested to reach the construction market as an available
486 solution. Hence, the comparison in this study shows that the potential carbon
487 reductions are higher for the strategies which deviate more from the traditional design
488 and construction practice of flat slabs. However, the present climate emergency
489 suggests that the construction industry should take multiple approaches to minimise
490 embodied carbon in concrete floor designs. Therefore, it is crucial in the upcoming
491 construction projects to parametrically optimise the designs, to compare conventional
492 alternatives available, and to move towards shape optimised floor systems.

493 Estimating environmental performance of different concrete floor solutions in this study
494 considered 'cradle-to-gate' embodied carbon, only the life cycle phases A1 to A3. Even
495 though the previous studies (Monahan and Powell, 2011; Li *et al.*, 2013; Nadoushani
496 and Akbarnezhad, 2015; Meneghelli, 2018; Moncaster *et al.*, 2018) demonstrated that
497 'cradle-to-gate' embodied carbon is responsible for around 70% to 90% of life cycle
498 embodied carbon, the different solutions considered in this study have differences in
499 other life cycle stages. The different conventional floor solutions considered have
500 different construction times, complexities of the formwork, and transportation needs.
501 Also, the state-of-the-art optimised floor systems are associated with complex shapes
502 without flat soffits and potential involvement with construction robotics. Also, this study
503 focused on designs for typical office floor loading, and the conclusions may be different
504 for buildings with different functionalities. Therefore, the findings presented in this study

505 are limited to the 'cradle-to-gate' phase, and future studies are needed to scrutinise the
506 effect of other life cycle phases. Furthermore, comparing the cost of the different low
507 carbon strategies is also important for the multi-objective optimisation of concrete
508 floors. However, the economic aspects have not been discussed in this scope since it
509 is challenging to compare the cost of construction techniques that have different levels
510 of maturity and availability in the present market.

511

512 **5 Conclusions**

513 Parametric design optimisation, alternative slab types, and novel optimised floor
514 systems have different levels of success in reducing embodied carbon in concrete
515 floors and need different levels of effort in implementation. The flat slab designs with
516 optimum embodied carbon coincide with minimum possible depth, which is often
517 governed by either fire criterion or deflection criterion. Parametric design optimisation
518 of slab thickness without changing the construction methods or material selection can
519 reduce embodied carbon by up to 8% for spans between 6 m and 10 m. Considering
520 lower grades of concrete in parametric optimisation can reduce embodied carbon up to
521 12% for spans less than 7 m, although the design depths are increased. Switching to
522 other conventional alternative slab types available in the market can further reduce
523 embodied carbon but the optimum slab type depends on the column spacing. Post-
524 tensioning flat slabs with column spacings more than 7 m can reduce embodied
525 carbon, and the benefit increases with the span, reaching 23% for 12 m spans. Moving
526 to two-way slabs on beams for spans less than 9 m or hollow-core slabs for longer
527 spans can cut embodied carbon by 21% to 36%. Much higher savings of embodied
528 carbon up to 65% can be achieved by adopting novel floor systems which transfer
529 loads through compressive membrane actions rather than flexure. The comparison of

530 the optimisation strategies considered in this scope suggested that the potential
531 savings of embodied carbon increased with the required level of modifications to the
532 conventional design and construction practice. Also, embodied carbon per unit floor
533 area for different carbon reduction strategies and the differences among them
534 increases with column spacing, highlighting the importance of optimising column
535 layout. Hence, the construction industry should move towards optimised floor systems
536 based on compressive membranes in future, while optimising the designs and
537 considering alternatives in the present context to effectively meet the carbon targets.

538

539 **6 Future Work**

540 Optimisation of flat slab designs should be further scrutinised concerning deflection
541 control since the design space was limited by the adjusted span/depth ratios in most of
542 the cases considered. Also, the effect of the life cycle phases beyond ‘cradle-to-gate’
543 for different optimisation strategies should be further investigated.

544

545 **7 Acknowledgement**

546 The authors would like to acknowledge the Churchill Jafar Studentship for PhD study at
547 the University of Cambridge.

548 **8 Appendix**

549 **Table A2: The Cradle-to-Gate Embodied Carbon Coefficients of The Building Materials**

Material	Carbon Coefficient
Steel (85% recycled)	1.20 kgCO ₂ e/kg (Circular Ecology, 2021)

Material	Carbon Coefficient
Glass Fibre Textile	3.00 kgCO ₂ e/kg (Hawkins, 2019)
C20/25 Concrete	0.112 kgCO ₂ e/kg (Circular Ecology, 2021)
C30/37 Concrete	0.132 kgCO ₂ e/kg (extrapolated)
C32/40 Concrete	0.138 kgCO ₂ e/kg (Circular Ecology, 2021)
C40/50 Concrete	0.159 kgCO ₂ e/kg (Circular Ecology, 2021)
C45/55 Concrete	0.171 kgCO ₂ e/kg (extrapolated)
C50/60 Concrete	0.180 kgCO ₂ e/kg (extrapolated)
Hollow-core panel 150 mm	50 kgCO ₂ e/m ² (The Concrete Centre, 2020)
Hollow-core panel 200 mm	57 kgCO ₂ e/m ² (The Concrete Centre, 2020)
Hollow-core panel 250 mm	65 kgCO ₂ e/m ² (The Concrete Centre, 2020)
Hollow-core panel 300 mm	75 kgCO ₂ e/m ² (The Concrete Centre, 2020)
Hollow-core panel 350 mm	85 kgCO ₂ e/m ² (The Concrete Centre, 2020)
Hollow-core panel 400 mm	95 kgCO ₂ e/m ² (The Concrete Centre, 2020)
Hollow-core panel 450 mm	105 kgCO ₂ e/m ² (The Concrete Centre, 2020)
Recycled Aggregate Fill	0.0061 kgCO ₂ e/kg (Circular Ecology, 2021)

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551

552 9 References

553 Block, P., Rippmann, M. and Van Mele, T. (2017) 'Compressive Assemblies: Bottom-

554 Up Performance for a New Form of Construction', 87(4), pp. 104–109. doi:

555 10.1002/ad.2202.

556 Bond, A. J. *et al.* (2019) *How to Design Concrete Structures using Eurocode 2*. 2nd

557 edn. London: The Concrete Centre.

558 British Cement Association (2001) 'Flat Slabs for Efficient Concrete Construction'.

559 de Brito, J., Kurda, R. and da Silva, P. R. (2018) 'Can We Truly Predict the
560 Compressive Strength of Concrete without Knowing the Properties of Aggregates?',
561 *Applied Sciences*, 8(7), p. 1095. doi: 10.3390/app8071095.

562 Brooker, O. (2009) *Concrete Buildings Scheme Design Manual*. Surrey: The Concrete
563 Centre.

564 BSI (2011) *BS EN 15978:2011: Sustainability of construction works - Assessment of*
565 *environmental performance of buildings Calculation method*. London: BSI.

566 BSI (2015) *BS EN 1992-1-1:2004+A1:2014: Eurocode 2 - Design of concrete*
567 *structures: Part 1-1: General rules and rules for buildings*. London: BSI.

568 Circular Ecology (2021) *Embodied Carbon - The ICE Database, Circular Ecology*.
569 Available at: <https://circularecology.com/embodied-carbon-footprint-database.html>
570 (Accessed: 8 October 2020).

571 Drewniok, M. P. (2021) *Relationships between building structural parameters and*
572 *embodied carbon Part 1: Early-stage design decisions. (ENG-TR.013)*. University of
573 Cambridge. doi: doi.org/10.17863/CAM.75783.

574 Eleftheriadis, S. *et al.* (2018) 'Investigating relationships between cost and CO2
575 emissions in reinforced concrete structures using a BIM-based design optimisation
576 approach', *Energy and Buildings*. Elsevier B.V., 166, pp. 330–346. doi:
577 10.1016/j.enbuild.2018.01.059.

578 Ferreiro-Cabello, J. *et al.* (2016) 'Minimizing greenhouse gas emissions and costs for
579 structures with flat slabs', *Journal of Cleaner Production*. Elsevier Ltd, 137, pp. 922–
580 930. doi: 10.1016/j.jclepro.2016.07.153.

581 Foraboschi, P., Mercanzin, M. and Trabucco, D. (2014) 'Sustainable structural design

582 of tall buildings based on embodied energy', *Energy and Buildings*. Elsevier B.V., 68,
583 pp. 254–269. doi: 10.1016/j.enbuild.2013.09.003.

584 Gibbons, O. P. and Orr, J. J. (2020) *How to calculate Embodied Carbon*. London:
585 IStructE. Available at: [https://www.istructe.org/resources/guidance/how-to-calculate-](https://www.istructe.org/resources/guidance/how-to-calculate-embodied-carbon/)
586 [embodied-carbon/](https://www.istructe.org/resources/guidance/how-to-calculate-embodied-carbon/).

587 Gieseke, J. *et al.* (2016) 'Construction sector views on low carbon building materials',
588 *Building Research & Information*, 44(4), pp. 423–444. doi:
589 10.1080/09613218.2016.1086872.

590 Goodchild, C. H., Webster, R. M. and Elliott, K. S. (2009) *Economic Concrete Frame*
591 *Elements to Eurocode 2*. Surrey: The Concrete Centre.

592 Hammond, G. P. and Jones, C. I. (2008) 'Embodied energy and carbon in construction
593 materials', *Proceedings of the Institution of Civil Engineers - Energy*, 161(2), pp. 87–98.
594 doi: 10.1680/ener.2008.161.2.87.

595 Hawkins, W. *et al.* (2019) 'Design, Construction and Testing of a Low Carbon Thin-
596 Shell Concrete Flooring System', *Structures*. Elsevier, 18(August 2018), pp. 60–71. doi:
597 10.1016/j.istruc.2018.10.006.

598 Hawkins, W. (2019) *Thin-shell concrete floors for sustainable buildings, Doctoral*
599 *Thesis*. University of Cambridge.

600 Hawkins, W. *et al.* (2020) 'A design methodology to reduce the embodied carbon of
601 concrete buildings using thin-shell floors', *Engineering Structures*. Elsevier,
602 207(September 2019), p. 110195. doi: 10.1016/j.engstruct.2020.110195.

603 Hawkins, W. (2020) *Design tables for thin-shell textile reinforced concrete floors*. Bath.
604 doi: 10.13140/RG.2.2.22183.57765/1.

605 IStructE (2017) *Manual for the design of concrete building structures to Eurocode 2*.
606 1.2. London: The Institution of Structural Engineers.

607 Jayasinghe, A. *et al.* (2021) 'Comparing the embodied carbon and cost of concrete
608 floor solutions', *Journal of Cleaner Production*. Elsevier Ltd, 324(October), p. 129268.
609 doi: 10.1016/j.jclepro.2021.129268.

610 Kaethner, S. C. and Burridge, J. A. (2012) 'Embodied CO₂ of structural frames',
611 *Structural Engineer*, 90(5), pp. 33–40. Available at:
612 [https://www.istructe.org/journal/volumes/volume-90-\(2012\)/issue-5/embodied-co2-of-](https://www.istructe.org/journal/volumes/volume-90-(2012)/issue-5/embodied-co2-of-structural-frames/)
613 [structural-frames/](https://www.istructe.org/journal/volumes/volume-90-(2012)/issue-5/embodied-co2-of-structural-frames/).

614 Kershaw, T. and Simm, S. (2014) 'Thoughts of a design team: Barriers to low carbon
615 school design', *Sustainable Cities and Society*. Elsevier B.V., 11(2014), pp. 40–47. doi:
616 10.1016/j.scs.2013.11.006.

617 Li, D. Z. *et al.* (2013) 'A methodology for estimating the life-cycle carbon efficiency of a
618 residential building', *Building and Environment*, 59, pp. 448–455. doi:
619 10.1016/j.buildenv.2012.09.012.

620 Liew, A. *et al.* (2017) 'Design, fabrication and testing of a prototype, thin-vaulted,
621 unreinforced concrete floor', *Engineering Structures*. Elsevier Ltd, 137, pp. 323–335.
622 doi: 10.1016/j.engstruct.2017.01.075.

623 Meneghelli, A. (2018) 'Whole-building embodied carbon of a North American LEED-
624 certified library: Sensitivity analysis of the environmental impact of buildings materials',
625 *Building and Environment*. Elsevier, 134(March), pp. 230–241. doi:
626 10.1016/j.buildenv.2018.02.044.

627 Miller, D., Doh, J. H. and Mulvey, M. (2015) 'Concrete slab comparison and embodied

628 energy optimisation for alternate design and construction techniques', *Construction and*
629 *Building Materials*. Elsevier Ltd, 80, pp. 329–338. doi:
630 10.1016/j.conbuildmat.2015.01.071.

631 Monahan, J. and Powell, J. C. (2011) 'An embodied carbon and energy analysis of
632 modern methods of construction in housing: A case study using a lifecycle assessment
633 framework', *Energy and Buildings*. Elsevier B.V., 43(1), pp. 179–188. doi:
634 10.1016/j.enbuild.2010.09.005.

635 Moncaster, A. M. *et al.* (2018) 'Why method matters: Temporal, spatial and physical
636 variations in LCA and their impact on choice of structural system', *Energy and*
637 *Buildings*. Elsevier B.V., 173, pp. 389–398. doi: 10.1016/j.enbuild.2018.05.039.

638 Nadoushani, Z. S. M. and Akbarnezhad, A. (2015) 'Effects of structural system on the
639 life cycle carbon footprint of buildings', *Energy & Buildings*. Elsevier B.V., 102, pp. 337–
640 346. doi: 10.1016/j.enbuild.2015.05.044.

641 Orr, J. *et al.* (2019) 'Minimising energy in construction : Practitioners' views on material
642 efficiency', *Resources, Conservation & Recycling*. Elsevier, 140(September 2018), pp.
643 125–136. doi: 10.1016/j.resconrec.2018.09.015.

644 Pan, W. and Pan, M. (2021) 'Drivers, barriers and strategies for zero carbon buildings
645 in high-rise high-density cities', *Energy and Buildings*. Elsevier B.V., 242, p. 110970.
646 doi: 10.1016/j.enbuild.2021.110970.

647 RICS (2017) *Whole life carbon assessment for the built environment Whole life carbon*
648 *assessment for the built environment*. London: Royal Institution of Chartered
649 Surveyors. Available at: [https://www.rics.org/uk/upholding-professional-](https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/)
650 [standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-](https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/)
651 [built-environment/](https://www.rics.org/uk/upholding-professional-standards/sector-standards/building-surveying/whole-life-carbon-assessment-for-the-built-environment/).

652 Rippmann, M. *et al.* (2018) 'Design, fabrication and testing of discrete 3D sand-printed
653 floor prototypes', *Materials Today Communications*. Elsevier, 15(June 2017), pp. 254–
654 259. doi: 10.1016/j.mtcomm.2018.03.005.

655 Sansom, M. and Pope, R. J. (2012) 'A comparative embodied carbon assessment of
656 commercial buildings', *Structural Engineer*, 90(10), pp. 38–49. Available at:
657 [https://www.istructe.org/journal/volumes/volume-90-\(2012\)/issue-10/research-a-](https://www.istructe.org/journal/volumes/volume-90-(2012)/issue-10/research-a-comparative-embodied-carbon-assessment/)
658 [comparative-embodied-carbon-assessment/](https://www.istructe.org/journal/volumes/volume-90-(2012)/issue-10/research-a-comparative-embodied-carbon-assessment/).

659 The Concrete Centre (2009) *Worked Examples to Eurocode 2: Volume 1*. Surrey: The
660 Concrete Centre.

661 The Concrete Centre (2020) 'Cost and Carbon: Concept V4'. London: The Concrete
662 Centre. Available at: [https://www.concretecentre.com/Publications-Software/Design-](https://www.concretecentre.com/Publications-Software/Design-tools-and-software/Concept-V4-Cost-and-Carbon.aspx)
663 [tools-and-software/Concept-V4-Cost-and-Carbon.aspx](https://www.concretecentre.com/Publications-Software/Design-tools-and-software/Concept-V4-Cost-and-Carbon.aspx).

664 The Concrete Society (2007) *Technical Report No. 64: Guide to the Design and*
665 *Construction of Reinforced Concrete Flat Slabs*. Surrey: The Concrete Society.

666 Trinh, H. T. M. K. *et al.* (2021) 'Environmental considerations for structural design of flat
667 plate buildings – Significance of and interrelation between different design variables',
668 *Journal of Cleaner Production*. Elsevier Ltd, 315(May), p. 128123. doi:
669 10.1016/j.jclepro.2021.128123.

670 UNFCCC (2017) *Bigger Climate Action Emerging in Cement Industry | UNFCCC, UN*
671 *Climate Change News*. Available at: [https://unfccc.int/news/bigger-climate-action-](https://unfccc.int/news/bigger-climate-action-emerging-in-cement-industry)
672 [emerging-in-cement-industry](https://unfccc.int/news/bigger-climate-action-emerging-in-cement-industry) (Accessed: 8 July 2020).

673