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Postdoctoral Placement Scheme
University of Cambridge

Technical Report:

Relationships between building structural parameters and embodied carbon

Part 1: Early-stage design decisions

Placement:
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ENG-TR.013

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1. Brief overview of the placement

The purpose of the placement was to assess the relationship between embodied carbon and the various structural requirements of a building design brief. The placement analysed both theoretical and real buildings to produce guidance that clarifies these relationships. The main focus of this placement was to find relationship between structural depth ver. spans, live loads and initial carbon intensity for different structural solutions (floor solutions). This report can be used as a design guidance to communicate relationships and inform future decisions as well as by designers to make informed design decisions and communicate the implications of the brief to clients.

2. Introduction

The construction of buildings and infrastructure make up a significant proportion of the global economy at around 13% of the global GDP [1]. Buildings and construction are responsible for almost 39% of energy-related carbon dioxide emissions and 36% of global energy use [2]. A quarter of these emissions in 2017 (3.8 $GtCO_2$) were connected to production, transport and use of construction materials for buildings. Cement and steel alone represented 6% of global CO_2 (2.0 $GtCO_2$) [3].
The UN predicts that global floor area will almost double to 415 bn m^2 by 2050 [4]. Around 70% of buildings by floor area are going to be constructed in countries that currently do not have any mandatory building energy codes [3]. Half of the new builds constructed by 2050 located in Western Europe and North America will represent non-residential buildings, adding 6% of buildings by floor area compared to 2017 [4].

To meet the global greenhouse gas (GHG) emission targets set by the 21st Conference of the Parties [5] enhancements in the material production and use across different industries are necessary [6, 7]. With increasing demand for new buildings and infrastructure, significant emission reduction strategies should be immediately implemented as using current emissions we will consume our remaining 2050 carbon budget within 12 years [2].

The environmental impact of the buildings depends on the materials and processes related to produce the building (embodied carbon/energy to practical completion/cradle-to-handover) [8, 9], operational energy that is needed during the service life (e.g. for lighting heating, cooling) [10] and embodied carbon/energy over the building life, connected to materials and processes related to maintenance, repair, replacement, refurbishment, as well as connected to the building end-of-life (e.g. demolition, materials disposal etc.). A whole life approach identifies the overall best combined opportunities for reducing life-time emissions, and also helps to avoid any unintended consequences of considering only embodied or operational and not considering them together over time [8, 11].

For an average office building located in London, each of them (initial embodied carbon, embodied carbon in use and operational carbon) represent 1/3 of whole life building emissions (Figure 1) [8, 12] and therefore whole-life impact should include all those three aspects. For a 50-year lifespan commercial building (design life-time according to the EC [13]) the structural frames represent 20-30% of whole-life carbon (WLC) [14-16], 40-60% of which represents slabs and floor beams [17] and 25% of which come from the columns [18]. Moving towards net-zero operational energy buildings, the embodied carbon connected to materials (initial and in use) will approach 100% of total emissions [11, 19] and therefore it is crucial to know how embodied carbon over the building life can be reduced to achieve “Net-zero whole-life carbon” building [12].

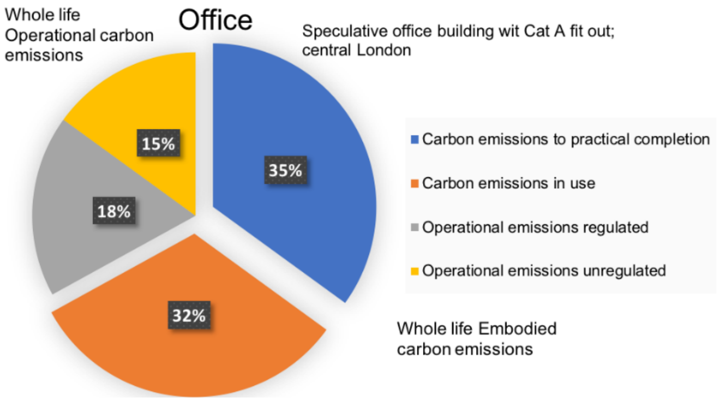


Figure 1 Whole-life carbon emissions for an average office building located in London [8] [12].

This report compares 5 different reinforced concrete (RC) floor solutions presenting carbon intensity for each solution, taking into account slab depth and reinforcement intensity per square meter of completed floor (without columns). Analysis was made for the span between 4.0-15.0 m and live loads 2.5, 5.0, 7.5 and 10.0 kN/m^2 respectively. This report presents Part 1 of the work.

3. Methodology

To present correlation between span, slab thickness and initial embodied carbon (cradle-to-gate) widely available for structural engineers' guidelines were used - "Economic Concrete Frame Elements to Eurocode 2" [20] and "How to design concrete structures using Eurocode 2" [21]. Additional structural calculations were made in compliance to Eurocode 0 [22], Eurocode 1 [23], Eurocode 3 [24] and Eurocode 4 [25].

Table 1 include the main assumptions taken for this exercise.

Table 1 Main assumptions

	Reinforced concrete floors
Units for embodied carbon	kgCO_2e/m^2
On-site concrete (unless stated otherwise)	C30/37
Pre-cast concrete	C40/50
Wet concrete density Dry concrete density	25 kN/m^3 24 kN/m^3
Live loads (kN/m^2)	2.5, 5.0, 7.5, 10.0
Spans (m)	4-15m
lx/ly ratio of bay	1 (square bays)
Carbon calculations boundaries	Initial embodied carbon (cradle-to-gate), Modules A1-A3
Support conditions (unless stated otherwise)	multi span
Floor layout	Square, 3 bays x 3 bays
Fire rating	60 min

Carbon calculations were based on the modular approach, within the system boundary presented on Figure 2. Initial embodied carbon used to produce materials and to fabricate structural elements (cradle-to-gate, Modules A1-A3) constitutes a significant part of the whole-life carbon impact and therefore in this report only this impact was assessed.

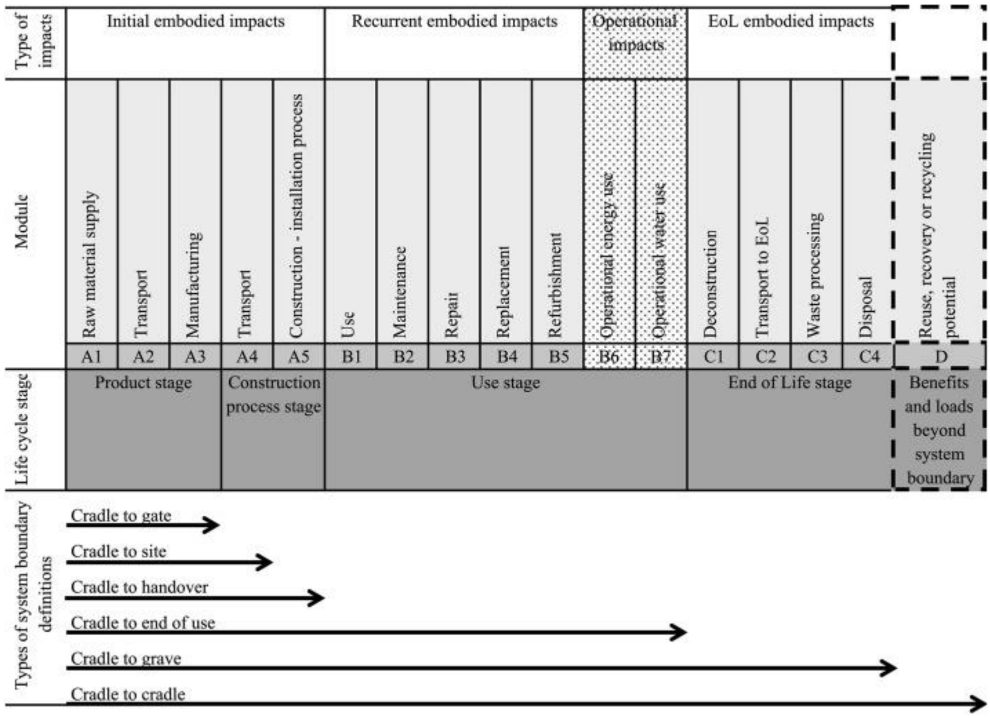


Figure 2 System boundaries definitions in relation to the life cycle stages of a building [26] [27]

To allow the comparison between different structural systems, fixed concrete mixed were assumed. Initial carbon values (cradle-to-gate), included in Table 2, were taken mainly from Inventory of Carbon and Energy (ICE) V3.0 Beta – 7 November 2019 [28]. Initial carbon for materials not included in ICE V3.0 was taken from Environmental Product Declarations (EPD) listed in Table 2.

Table 2 Initial carbon assumptions

Material	kgCO2e/m2	Source
C30/37 – CEM I + 20% GGBS (min cement content from BS8500-1:2016)	201 $kgCO_{2e}/m^3$ 84 $kgCO_{2e}/t$	ICE 3.0 [28]
C32/40 – CEM I + 20% GGBS (min cement content from BS8500-1:2016)	201 $kgCO_{2e}/m^3$ 84 $kgCO_{2e}/t$	ICE 3.0 [28]
C40/50 – CEM I + 20% GGBS (min cement content from BS8500-1:2016)	228 $kgCO_{2e}/m^3$ 97 $kgCO_{2e}/t$	ICE 3.0 [28]
Reinforcement	1450 kg CO_{2e}/t	ICE 3.0 [28] assuming 70% recycled content
Hollowcore slabs: 150mm (300 kg/m^2, 2000 kg/m^3) 200mm (340 kg/m^2, 1700 kg/m^3) 250mm (390 kg/m^2, 1560 kg/m^3) 300mm (450 kg/m^2, 1500 kg/m^3) 350mm (510 kg/m^2, 1457 kg/m^3) 400mm (570 kg/m^2, 1425 kg/m^3) 450mm (630 kg/m^2, 1400 kg/m^3) Topping, 50mm, C30/37 (CEM I + 20 % GGBS), reinforcement 0.4%	 50.2 $kgCO_{2e}/m^2$ 57.0 $kgCO_{2e}/m^2$ 65.3 $kgCO_{2e}/m^2$ 75.3 $kgCO_{2e}/m^2$ 85.4 $kgCO_{2e}/m^2$ 95.3 $kgCO_{2e}/m^2$ 105.4 $kgCO_{2e}/m^2$ 11.2 $kgCO_{2e}/m^2$	 EPD (for 150mm, 200-450mm – recalculated according to UK Precast Concrete Hollowcore Flooring) (http://bit.ly/2GSX6cr)

4. Reinforced Concrete Slabs

The most popular RC floor type in the UK both for residential and commercial buildings is flat slab. Nevertheless, in this section other solutions were compared according to slab depth for different span and live load, reinforcement content as well as carbon intensity of chosen solution. Comparison was made between flat slabs, two-way solid slab (both with and without beams), post-tensioned slabs, composite hollowcore with 50mm structural topping (both with and without beams), hollowcore without structural topping (both with and without beams) and waffle slabs. All main assumptions and material quantities were taken from tables included in "Economic Concrete Frame Elements to Eurocode 2" [ECFE] [20] as they include assumption to get the best economic solution. The best economic solution is correlated with the material quantities and therefore initial embodied carbon intensity (Figure 3). Calculations were also according to "How to design concrete structures using Eurocode 2" [21]. All slabs, if not stated otherwise, were taken as multi-span. All additional assumptions were presented in each section separately.

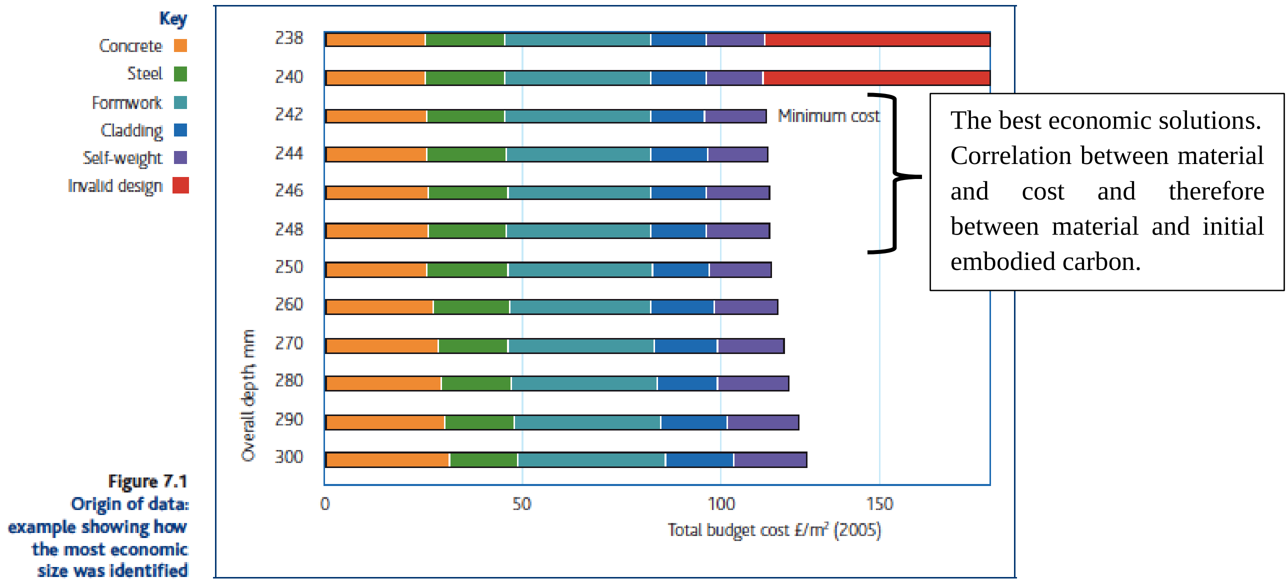


Figure 3 Figure 7.1. from ECFE – Origin of data: example showing how the most economic size was identified [20]

The results from this project were used to update the publicly available the conceptual design tool CONCEPT developed by MPA The Concrete Centre. Cost and Carbon: CONCEPT V4 can be used to compare costs and carbon of concrete frame options [29], and include: flat slabs, post-tensioned flat slabs, one-way slabs, ribbed slabs, troughed slabs precast hollowcore floors, two-way slabs.

To allow the comparison between different structural systems, fixed concrete mixed were assumed. This approach is a simplification because the miminum slab thickness is not always the solutions to get the lowest initial embodied carbon per m^2. The optimum thickness to minimise initial embodied carbon per m^2 can vary with the proportion of cement replacement. As an example, the higher cement replacement the importance of the reinforcement might increase; the higher cement replacement, the deeper slab we might have to design. Also, for some solutions such as post-tensioned slabs 15% of cement replacement might be a limiting value whereas for flat slabs higher than 20% the replacement might be common.

Nevertheless, this analysis presents the differences between the commonly used reinforced concrete solutions to allow for early design decisions such as span, live load and type of slab solution.

4.1. Flat slabs

4.1.1. Simply supported flat slabs

Figure 4 reproduced from [21] present the span-to-effective depth ratios and percentage of tension reinforcement that ensure simply supported flat slab deflection to be limited to span/250. Even if flat slabs ought to be designed as multi span slabs, Figure 4 is usually taken in the early design stage to quantify material volumes. Figure 4 covers concrete strength range from C20/25 to C50/60. Limiting span-to-depth ratio, next to assessment of the theoretical deflection using the expressions given in the Eurocode, is the method that can be used to ensure that deflections are not exceeded over span/250. For assumed standard fire resistance (60 min – the main assumption) that forces minimum slab thickness (180 mm – Table 2, pp. 52 [21]).

Figure 5 presents carbon intensity (cradle-to-gate) of simply supported flat slab for different span (square bays covering the range from 5x5 to 12x12). Slab depth in each case starts from 180 mm. Example of calculations are included below the

Figure 5.

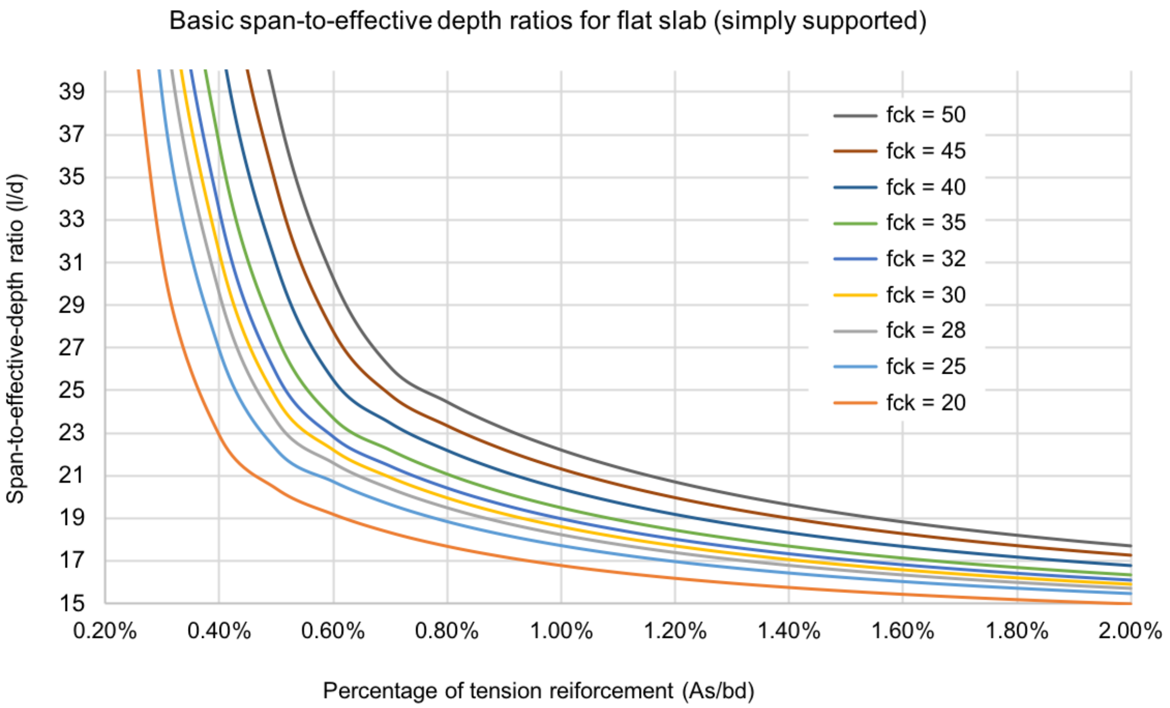


Figure 4 Basic span-to-effective-depth ratios for flat slabs according to "How to Design Concrete Structures using Eurocode 2" Figure 4, pp. 54 from [21]

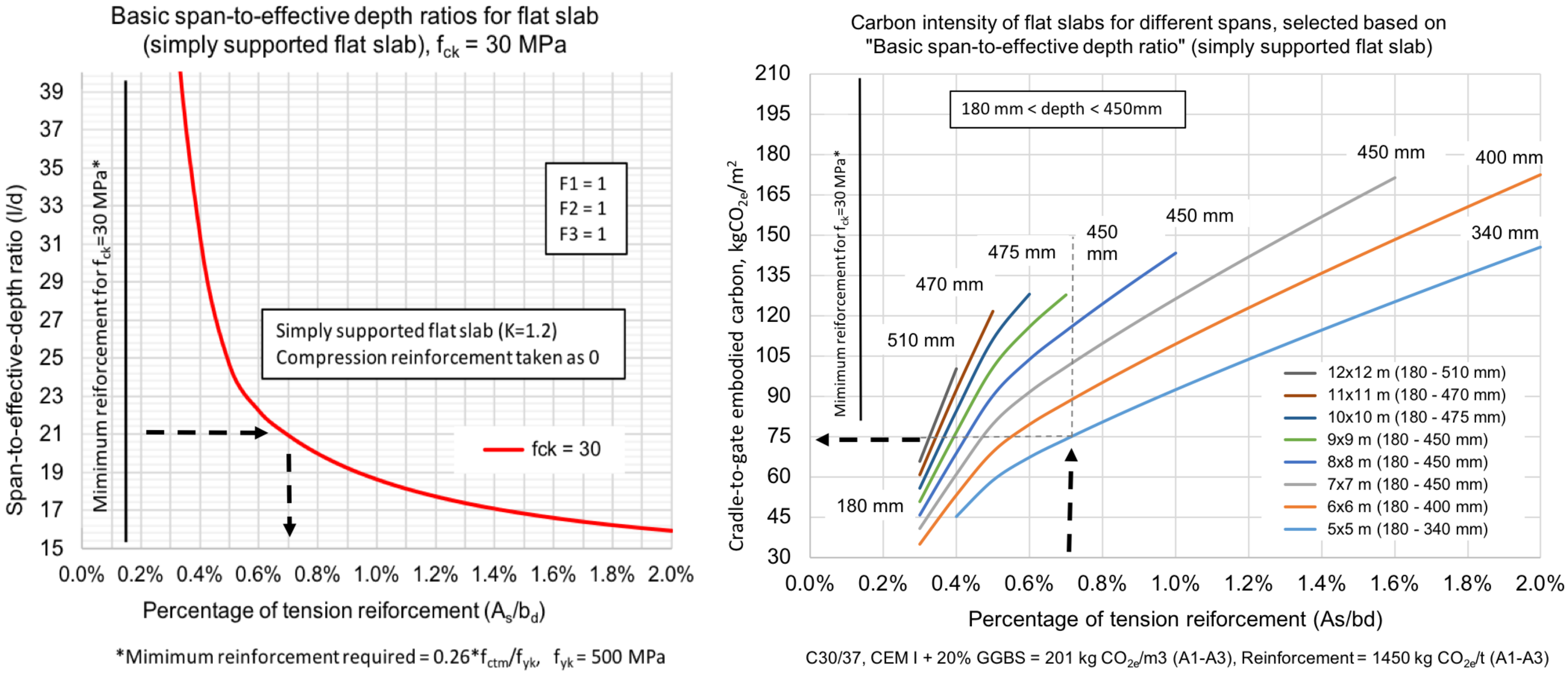


Figure 5 Basic span-to-effective-depth ratios for flat and initial carbon intensity

<u>Check:</u>

Check for the span 5x5 m

l = 5.0 m
Span to effective depth (l/d) ratio = 21
d = 5/21 = 0.238 m
h = d + a
a = 0.025 m (assumed)
h = 0.263 m (slab depth)

For l/d = 21, percentage of reinforcement – 0.7% (left graph)

Carbon calculations:
Concrete volume: 5.0 m x 0.263 m x 5.0 m = 6.58 m^3

Steel area: 0.263 m x 5.0 m x 0.7% = 0.0092 m^2

Steel volume: 0.0092 m2 x 5.0 m = 0.046 m^3
Steel tonnage: 0.046 m3 x 7.85 t/m^3 = 0.36 t, (14.4 kg/m2, 54.7 kg/m^3)

Carbon per m2:
[6.58m^3 (concrete) x 201 kgCO_{2e}/m^3 + 0.36t (steel) x 1450 kgCO_{2e}/t] / (5x5) = 73.78 kgCO_{2e}/m^2]

On the right graph, for span 5x5 we can find ~73 kgCO_{2e}/m^2.

For span 7x7 or other we have to pick % of reinforcement and find carbon intensity

For 7x7, and 0.7% or reinforcement, the result is 90 kgCO_{2e}/m^2 (on the right). To find depth we have to return to left graph and based on l/d find a effective-depth. Then add assumed a = 0.025 m.

4.1.2. Multi span flat slabs

All slab depths and reinforcement density were taken from "Economic Concrete Frame Elements to Eurocode 2" (Section 3.1.10, pp. 38-39) [20]. Calculations do not include columns.

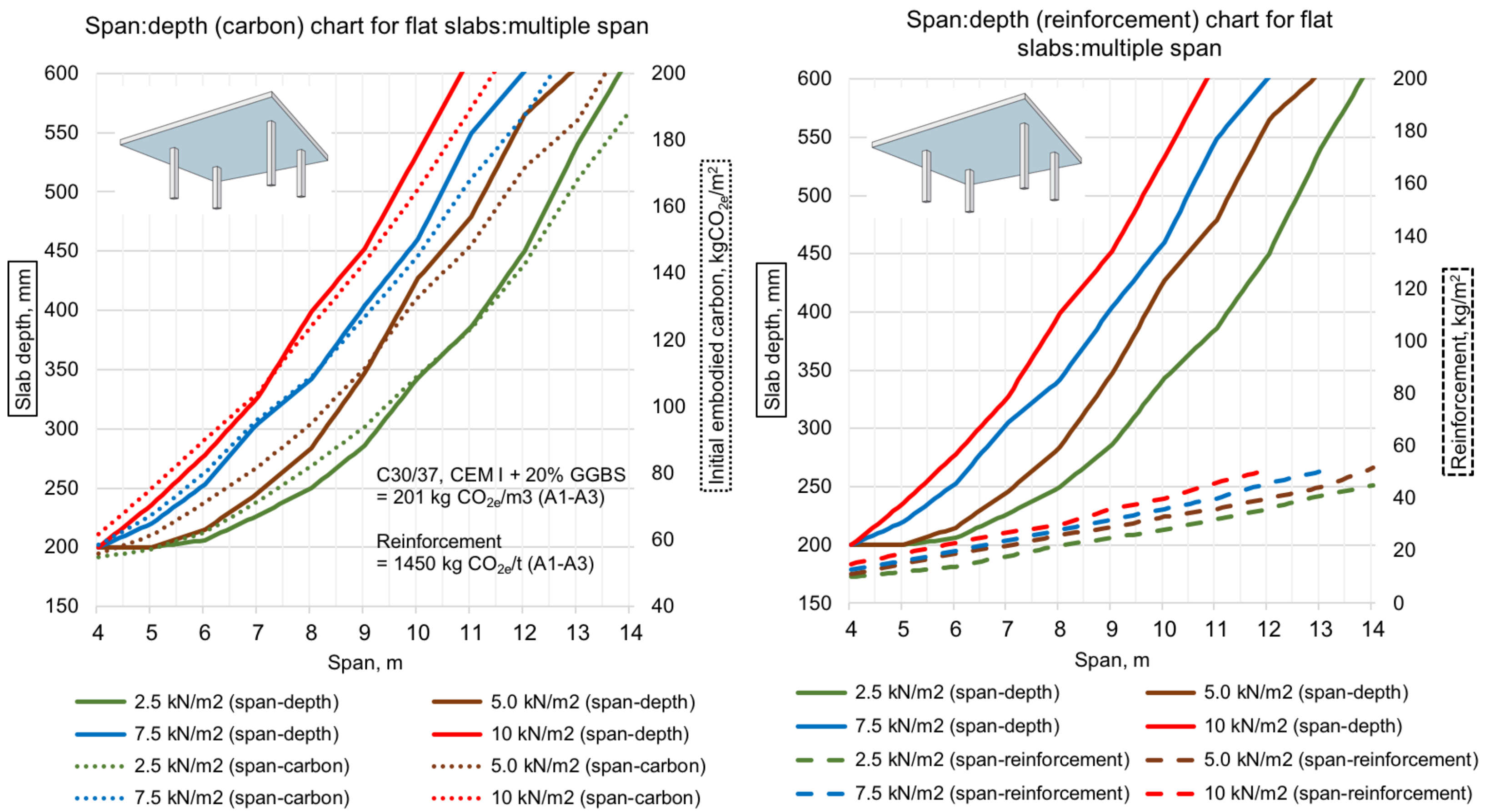
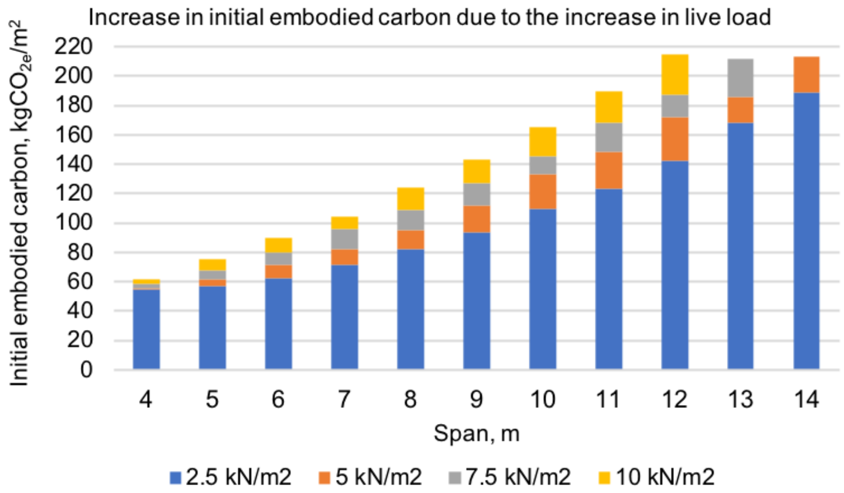
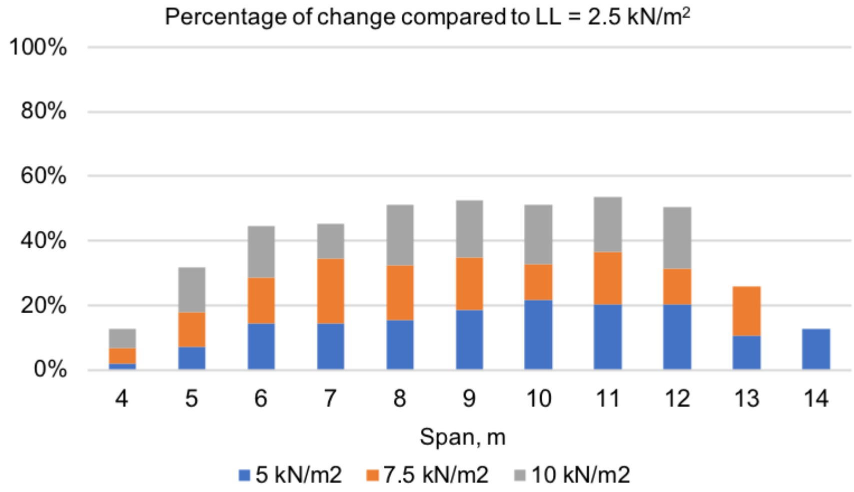


Figure 6 Span:slab depth and span:slab initial carbon – left, span:slab depth and span:reinforcement – right, flat slabs – multiple span





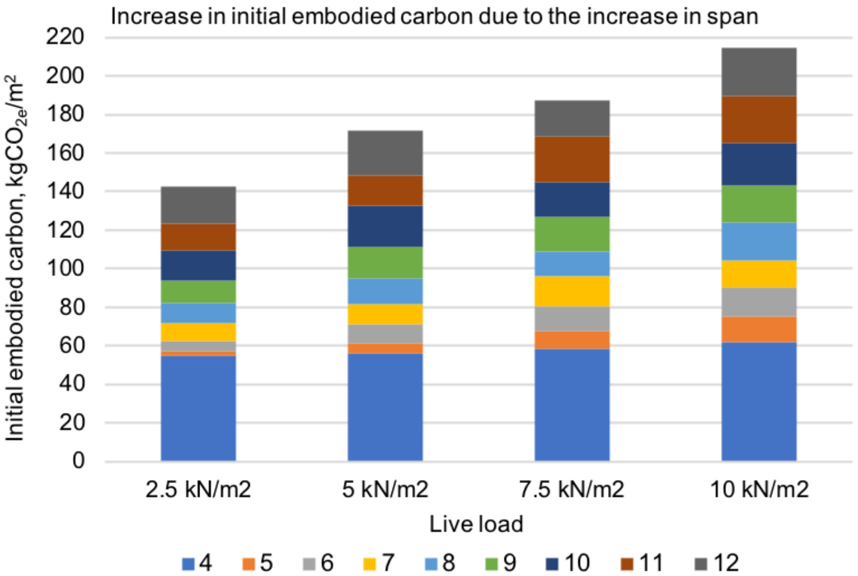


Figure 7 Flat slabs – increase in initial carbon due to the increase in live load (top), percentage of carbon change compared to LL=2.5 kN/m² (middle), increase in initial embodied carbon due to the increase in span (bottom)

4.2. Two-way solid slabs

All slab depths and reinforcement density were taken from "Economic Concrete Frame Elements to Eurocode 2" (Section 3.1.9., pp. 36-37) [20]. Calculations do not include columns.

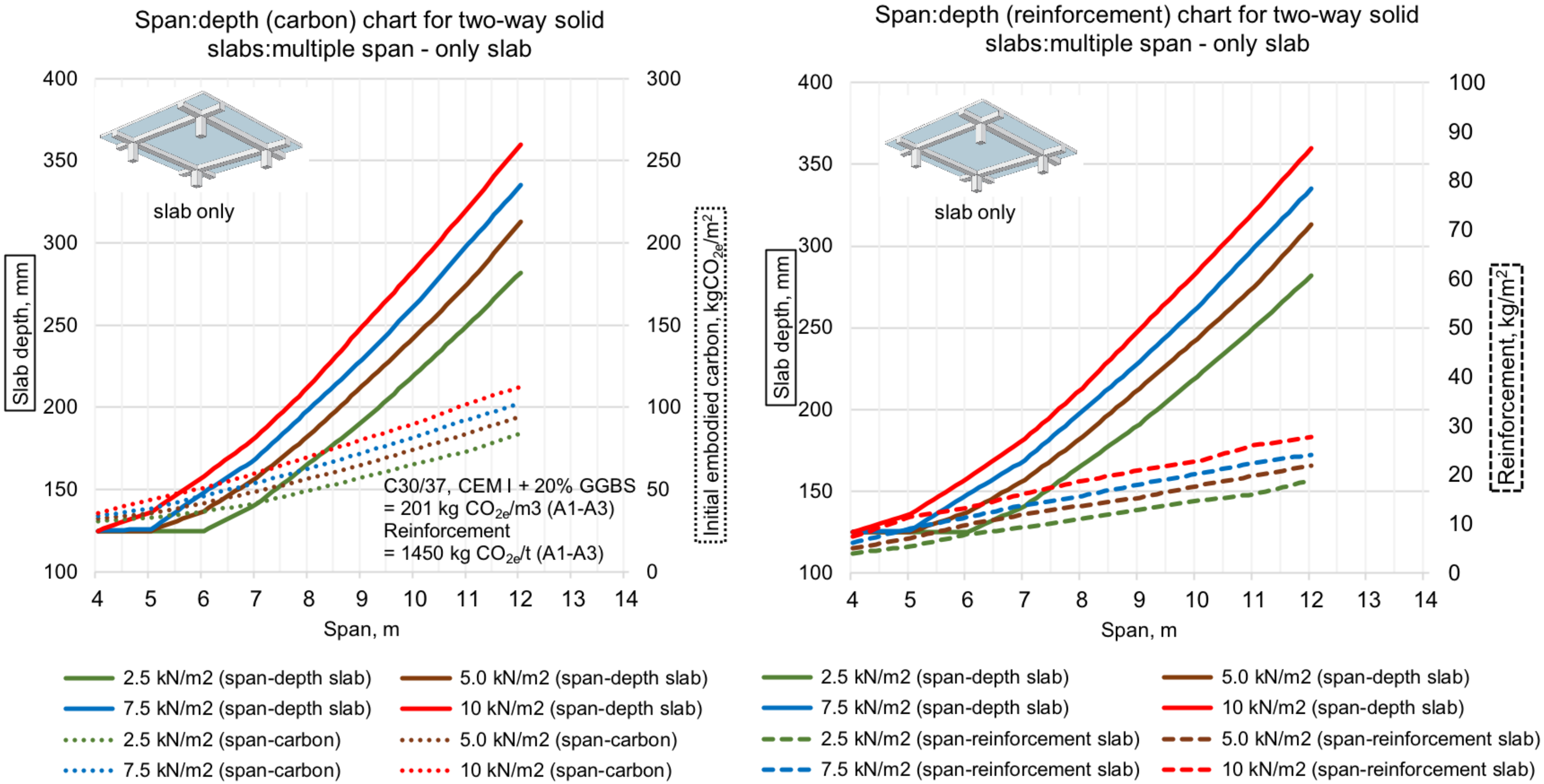
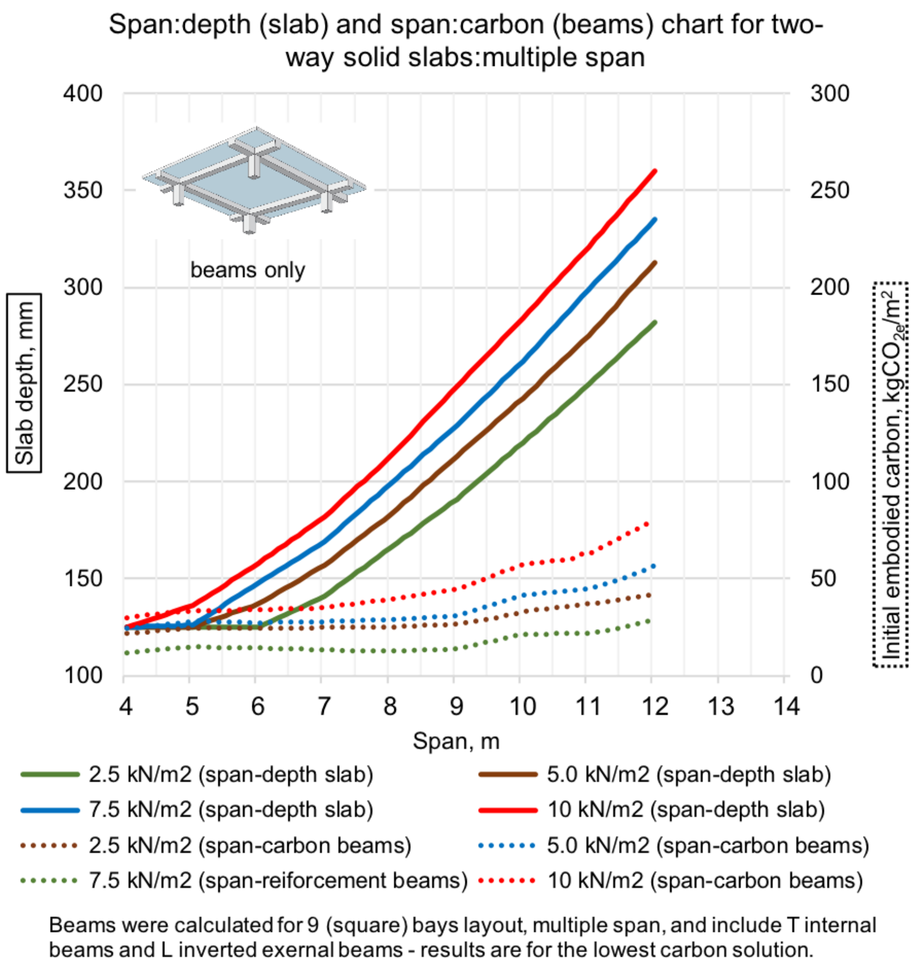


Figure 8 Span:slab depth and span:initial embodied carbon – left, span:slab depth and span:slab reinforcement – right, two-way solid slab – multiple span – SLAB ONLY

All beams sizes and reinforcement density were taken from "Economic Concrete Frame Elements to Eurocode 2" (Chapter 3.2. pp.44-71). Calculations include the lowest carbon solution for multiple-span T-beams (internal) with width 300, 450, 600 and 900 mm, and the depth in range between 250 – 900 mm.



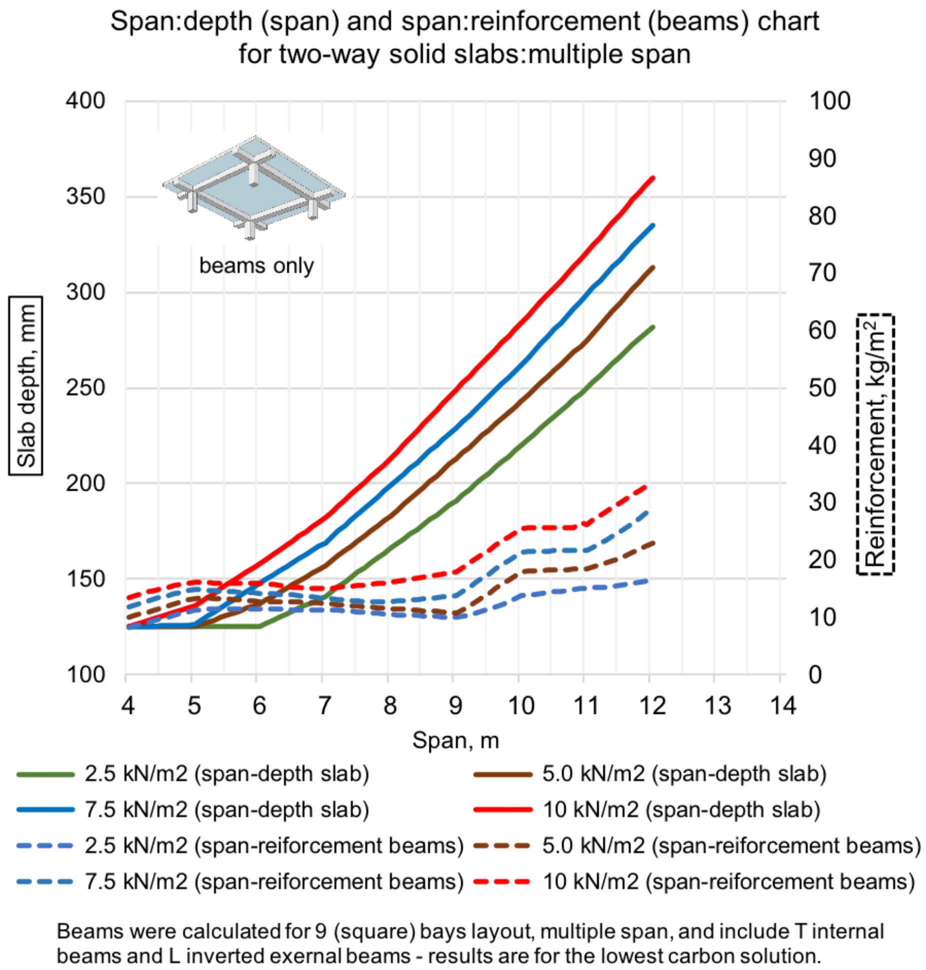
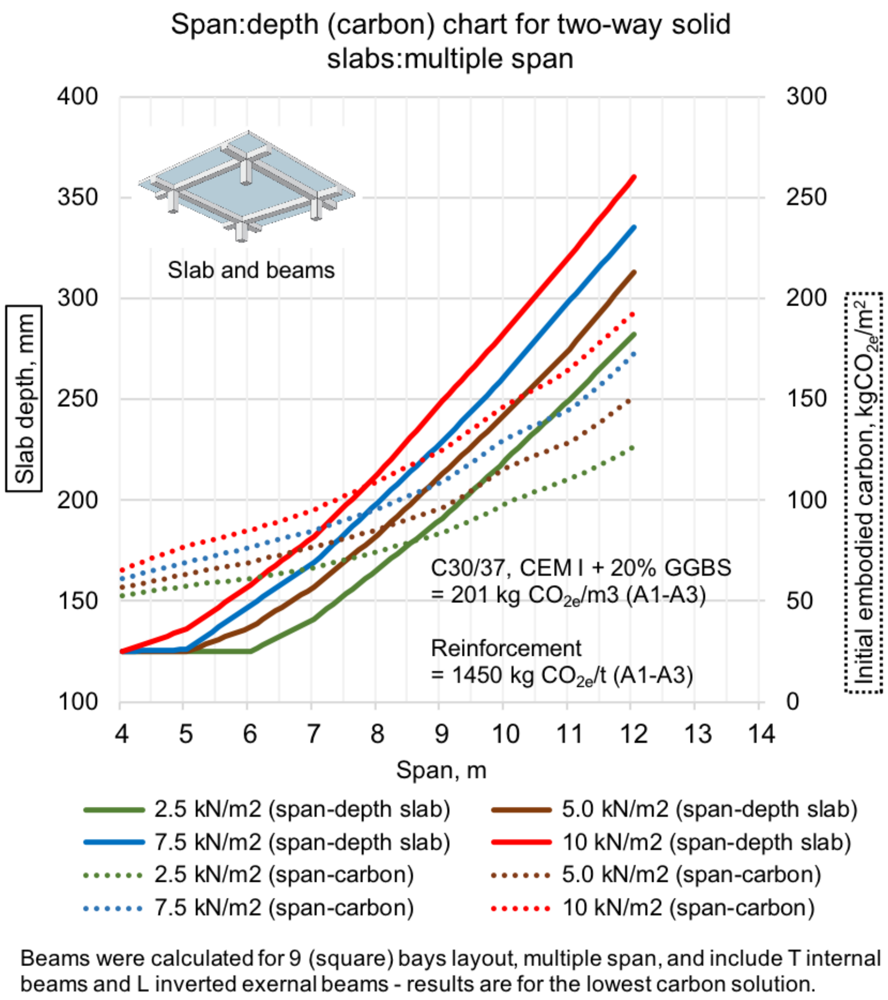


Figure 9 Span:slab depth and span:beams - initial embodied carbon – left, span:slab depth and span:beams reinforcement – right, two-way solid slabs– multiple span



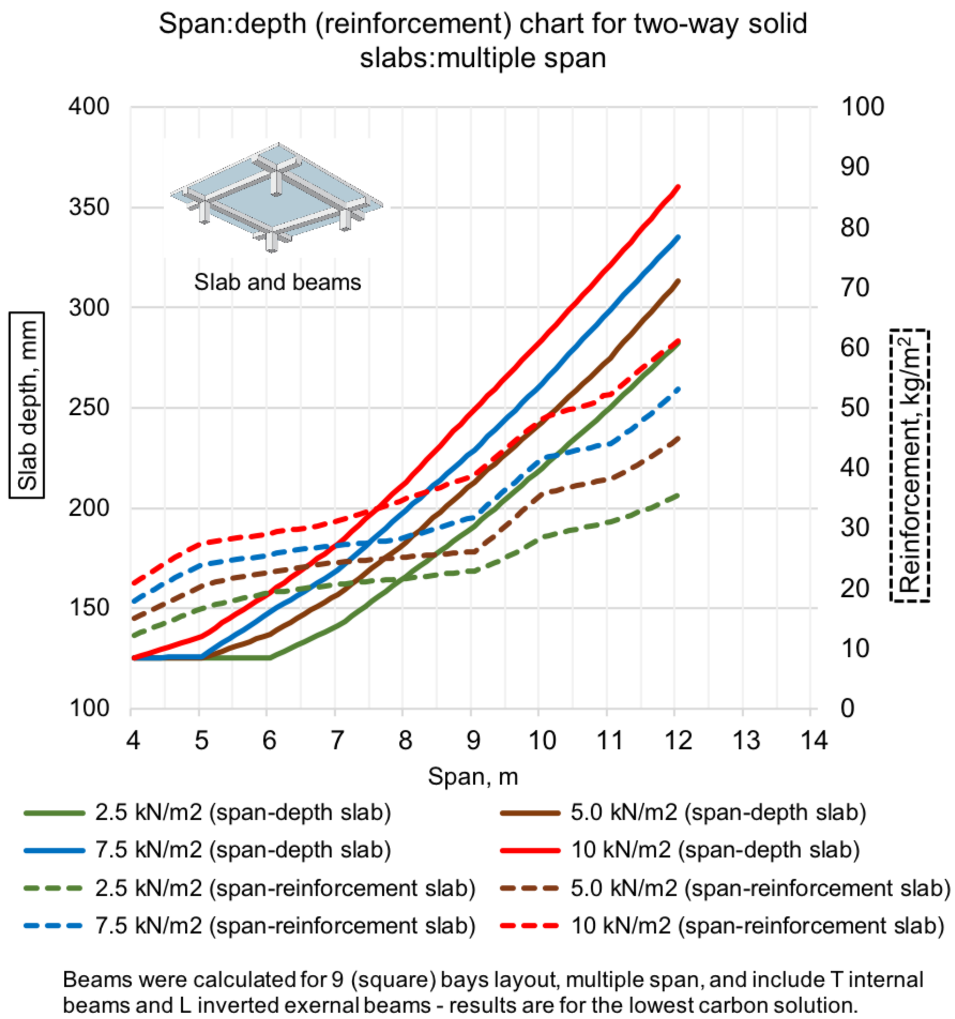
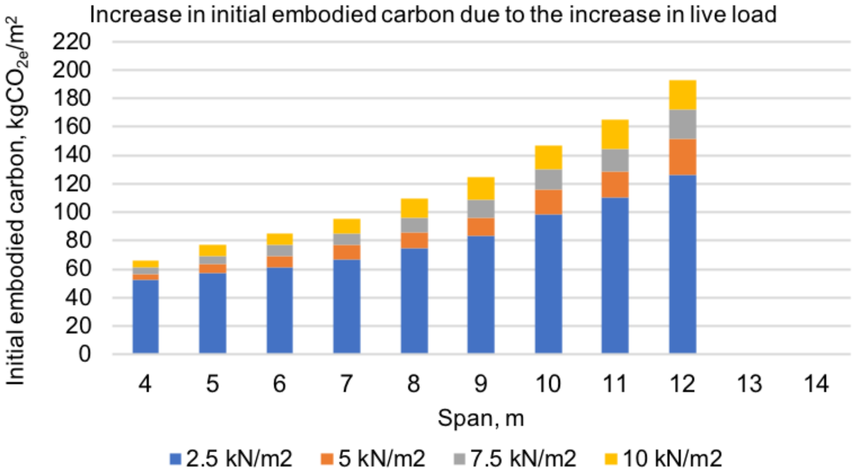
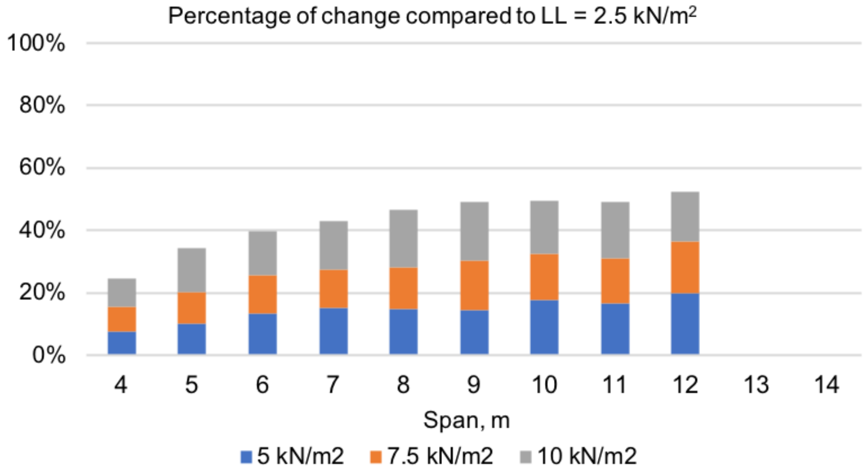


Figure 10 Span:slab depth and span:carbon (slab+beams) – left, span:slab depth and span:reinforcement (slab+beams) – right, two-way solid slabs– multiple span





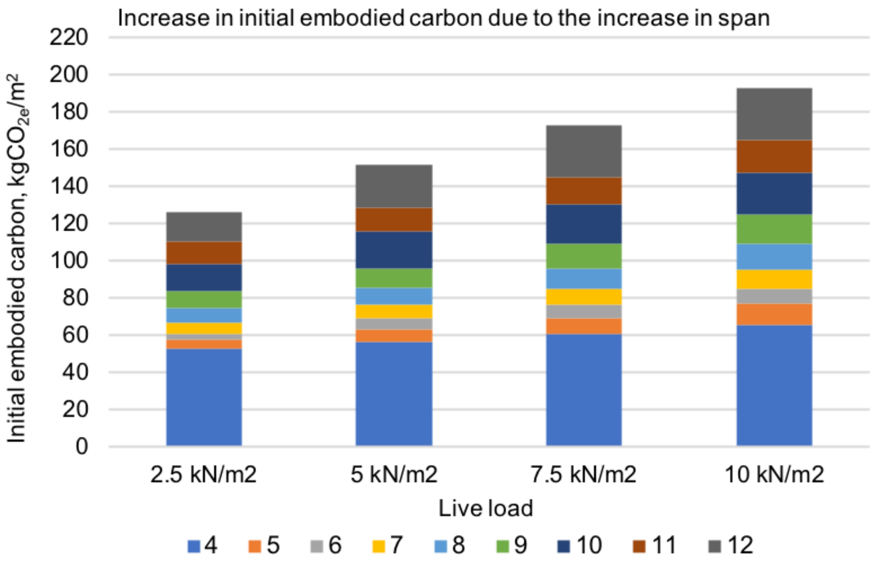
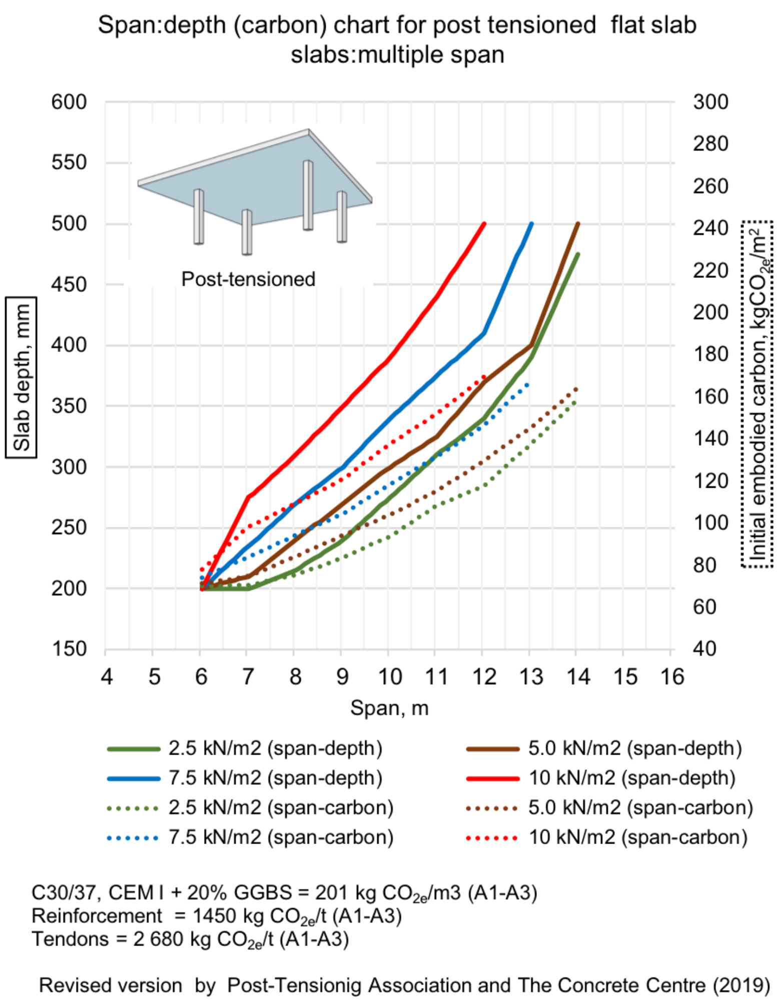


Figure 11 Two-way solid slabs with beams – increase in initial embodied carbon due to the increase in live load (top), percentage of initial embodied carbon change compared to LL=2.5 kN/m^2 (middle), increase in initial embodied carbon due to the increase in span (bottom)

4.3. Post-tensioned slabs

All slab depths and reinforcement density were taken from revised figures from the Post-Tensioning Association and the Concrete centre in January 2020.



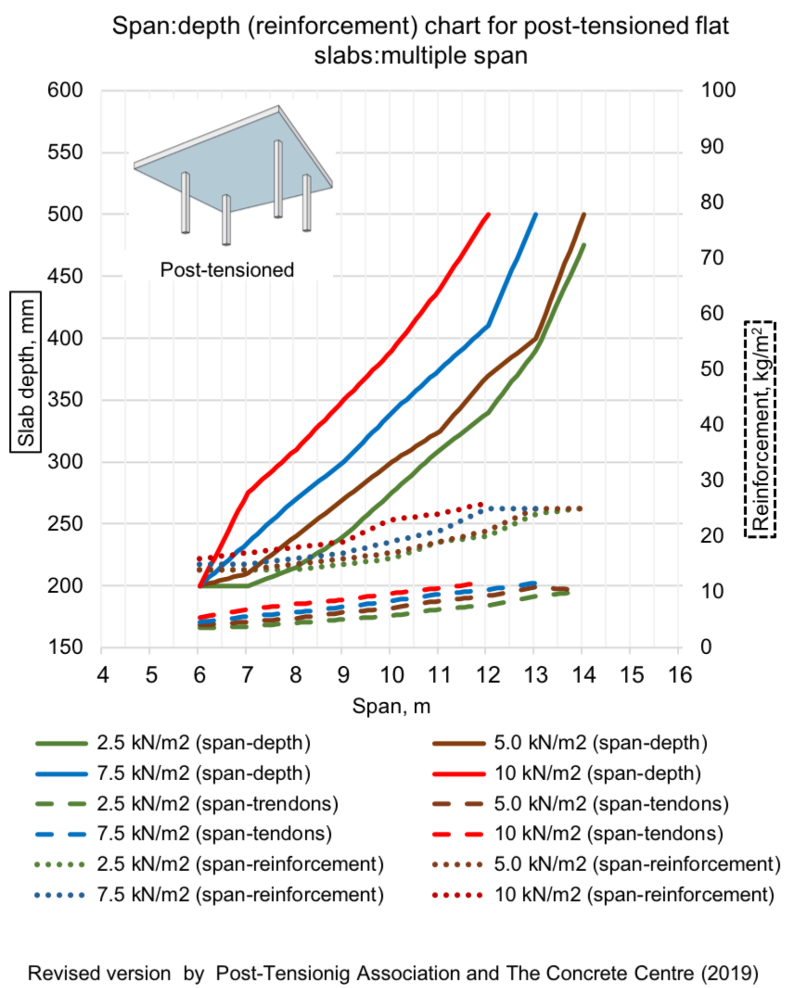


Figure 12 Span:slab depth and span:slab initial embodied carbon – left, span:slab depth and span:slab reinforcement – right, post-tensioned slabs – multiple span

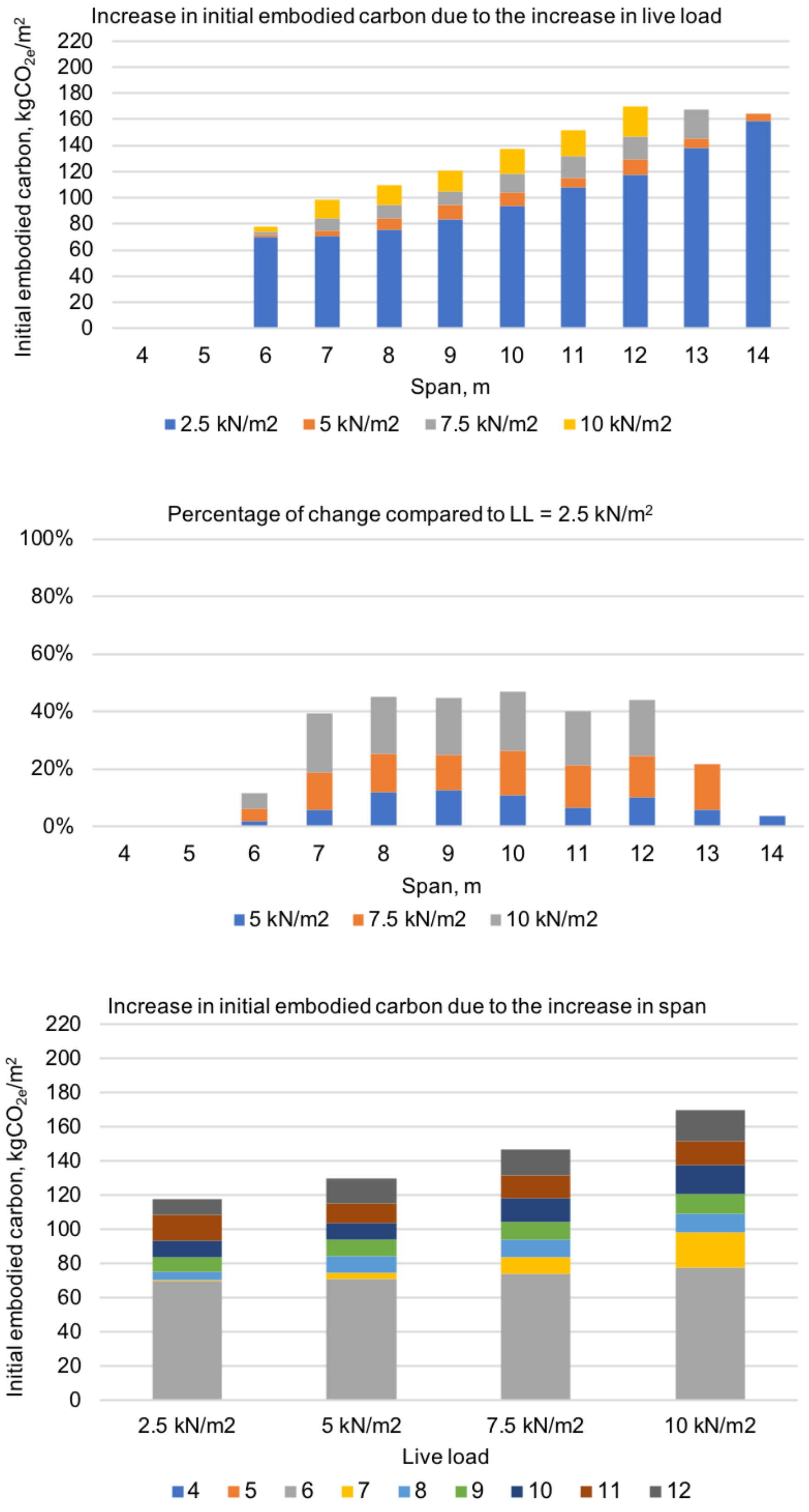
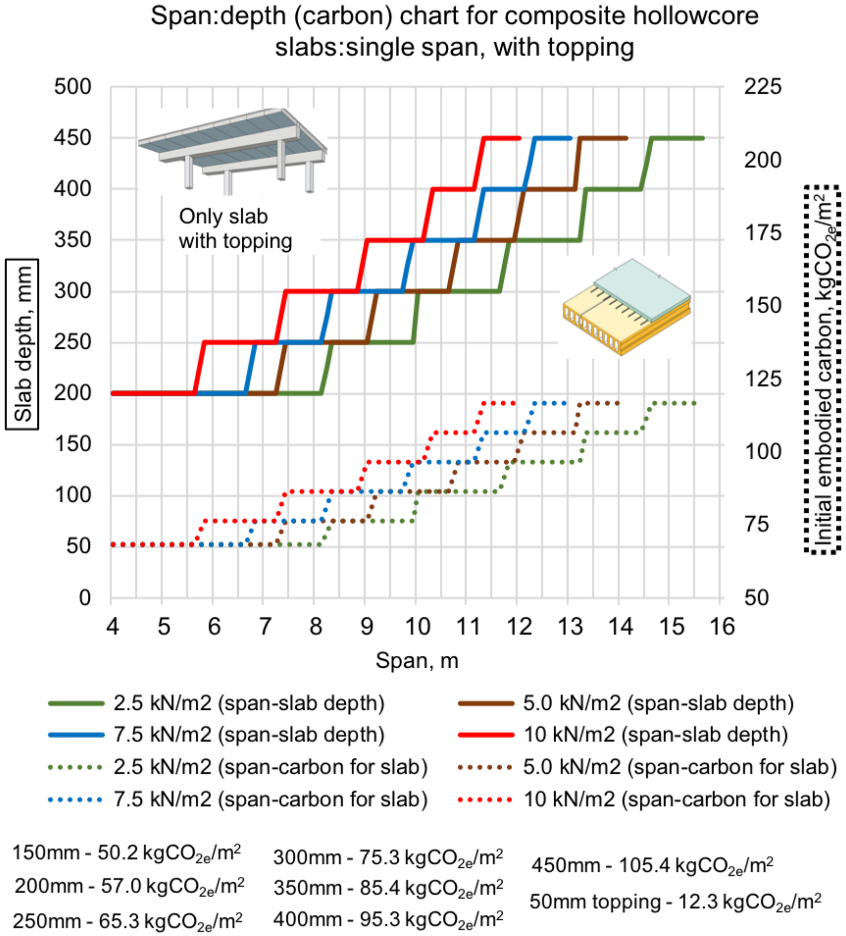


Figure 13 Post-tensioned slabs – increase in initial carbon due to the increase in live load (top), percentage of initial embodied carbon change compared to LL=2.5 kN/m² (middle), increase in initial embodied carbon due to the increase in span (bottom)

4.4. Hollowcore slabs – single span, only slab

All slab depths were taken from "Economic Concrete Frame Elements to Eurocode 2" (Sections 4.1.7. and 4.1.8. pp. 94-97) [20]. Calculations do not include columns.



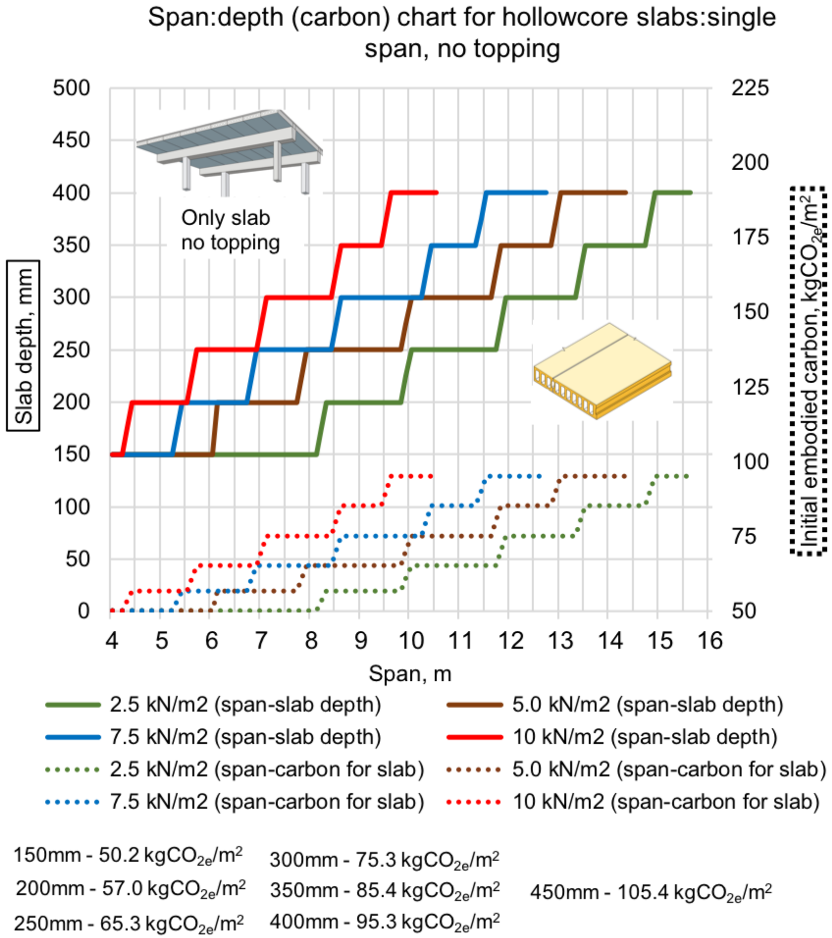


Figure 14 Span:slab depth and span:slab initial embodied carbon – composite hollowcore with 50mm structural topping, propped (left), hollowcore without structural topping, unpropped (right)

All precast beams sizes and reinforcement density were taken from “Economic Concrete Frame Elements to Eurocode 2” (Sections 4.2.5. and 4.2.6, pp. 108-109) and include rectangle beams with a width either 300 or 450 mm, and depth between 300 to 850 mm - results are for the lowest carbon solution (end – external beams)

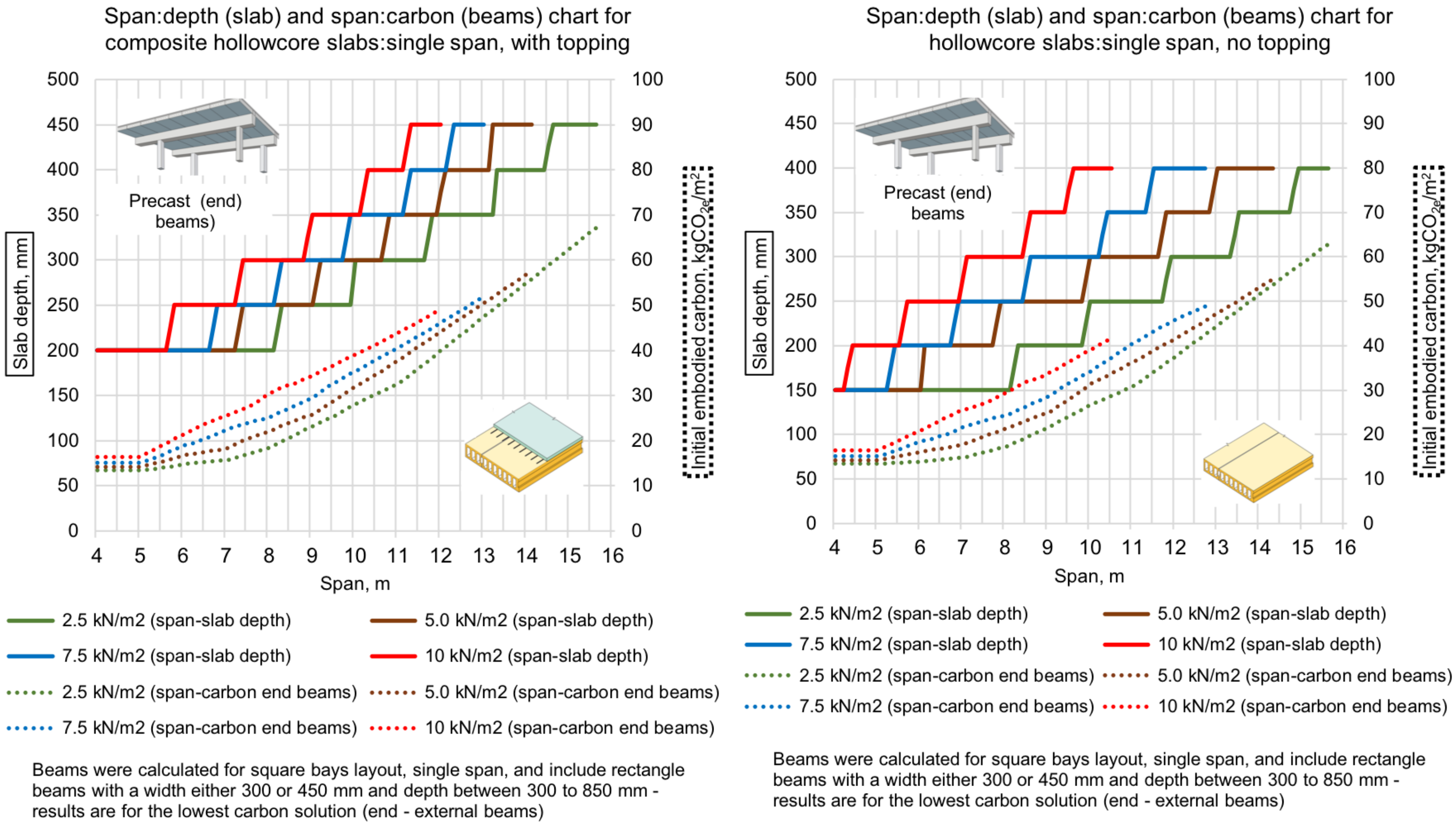
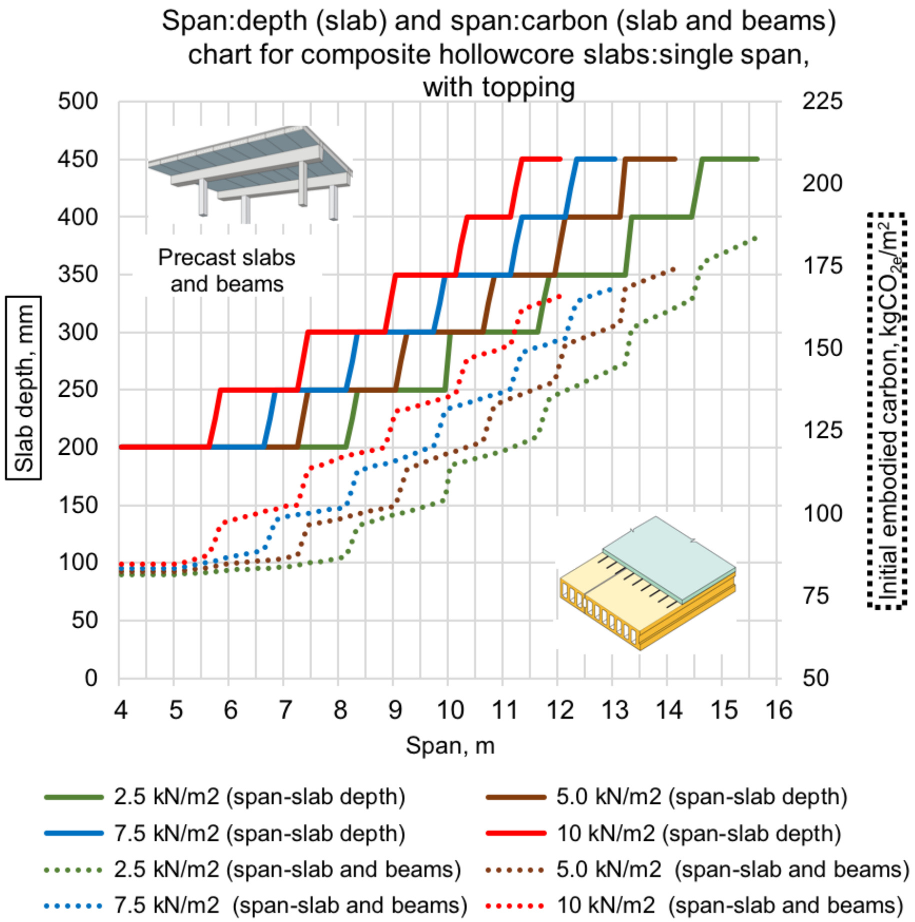
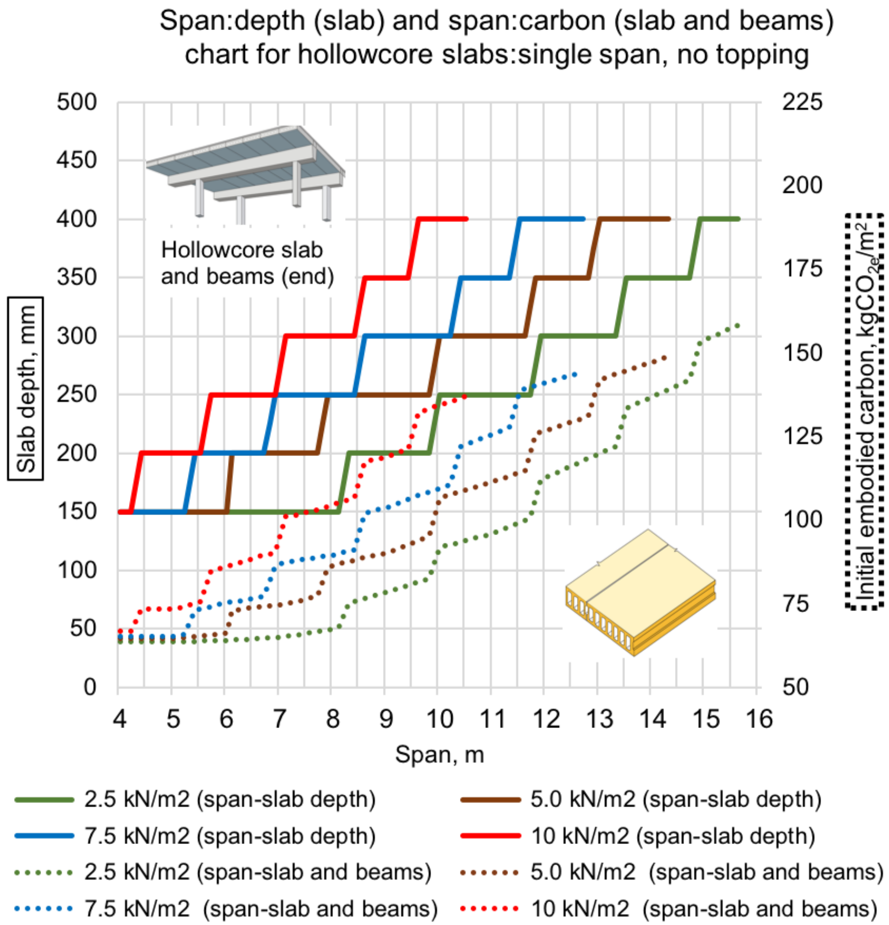


Figure 15 Span:slab depth and span:beam - initial embodied carbon – composite hollowcore with 50 mm structural topping, propped (left), hollowcore without structural topping, unpropped (right)

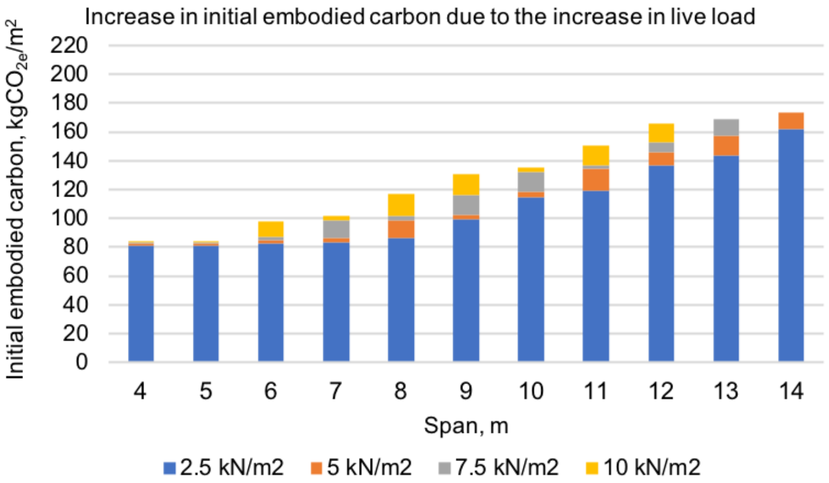


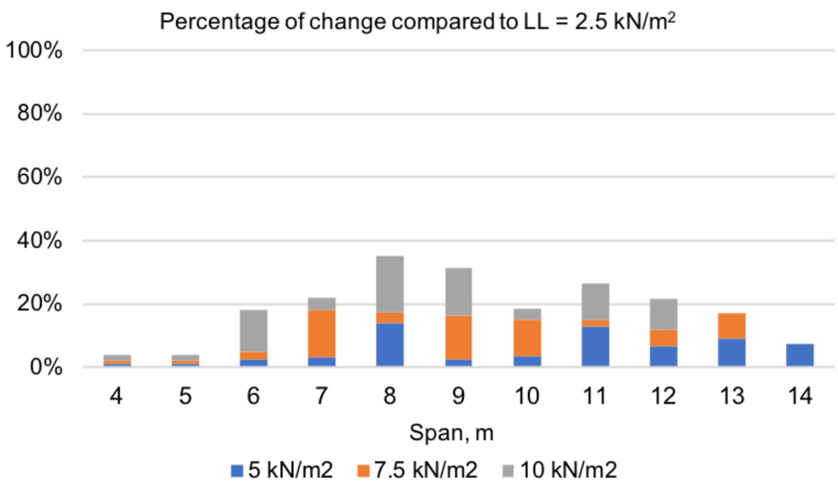
Beams were calculated for square bays layout, single span, and include rectangle beams with a width either 300 or 450 mm and depth between 300 to 850 mm - results are for the lowest carbon solution (end - externeal beams)



Beams were calculated for square bays layout, single span, and include rectangle beams with a width either 300 or 450 mm and depth between 300 to 850 mm - results are for the lowest carbon solution (end - externeal beams)

Figure 16 Span:slab depth and span: initial embodied carbon (slab + beams) – composite hollowcore with 50 mm structural topping, propped (left), hollowcore without structural topping, unpropped (right)





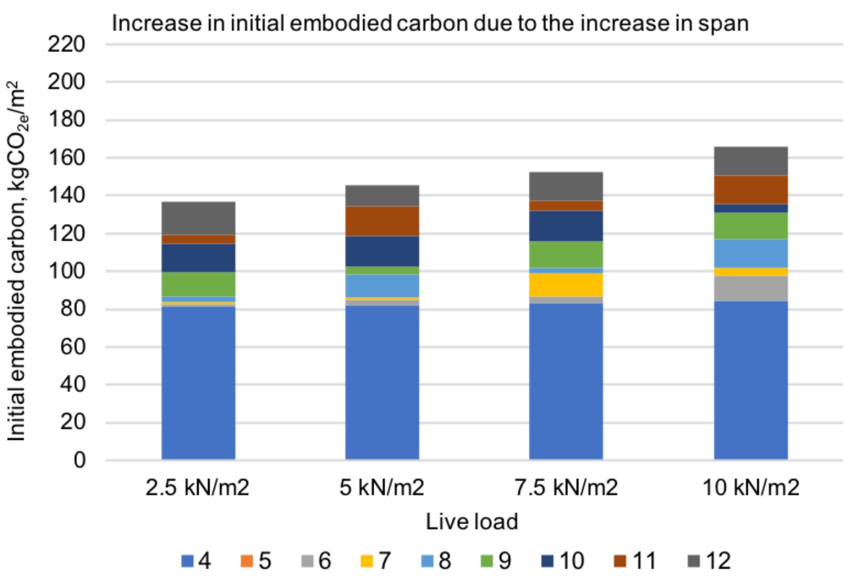


Figure 17 Composite hollowcore with 50 mm structural topping – increase in initial carbon due to the increase in live load (top), percentage of initial embodied carbon change compared to LL=2.5 kN/m² (middle), increase in initial embodied carbon due to the increase in span (bottom)

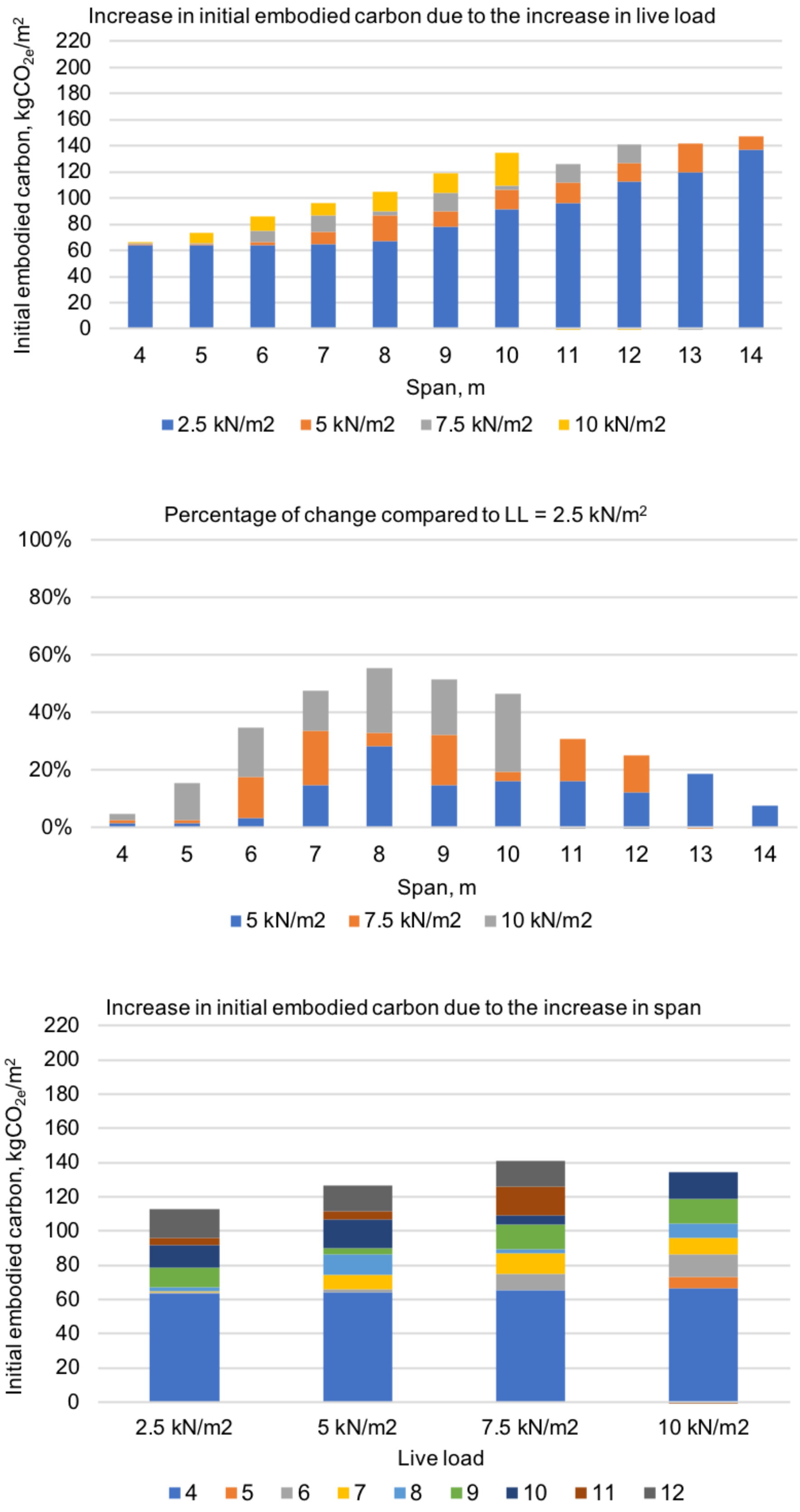
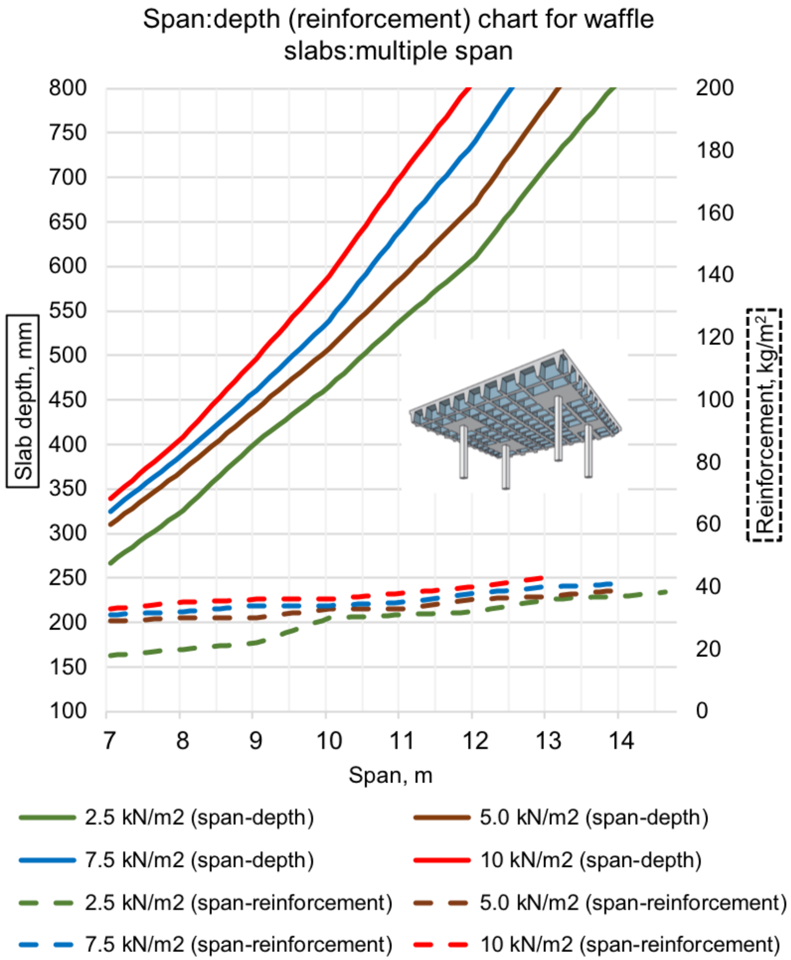


Figure 18 Hollowcore without structural topping, unpropped – increase in initial carbon due to the increase in live load (top), percentage of initial embodied carbon change compared to LL=2.5 kN/m² (middle), increase in initial embodied carbon due to the increase in span (bottom)

4.5. Waffle slabs

All slab depths and reinforcement density were taken from "Economic Concrete Frame Elements to Eurocode 2" (Section 3.1.12., pp. 42-43) [20]. Calculations do not include columns.



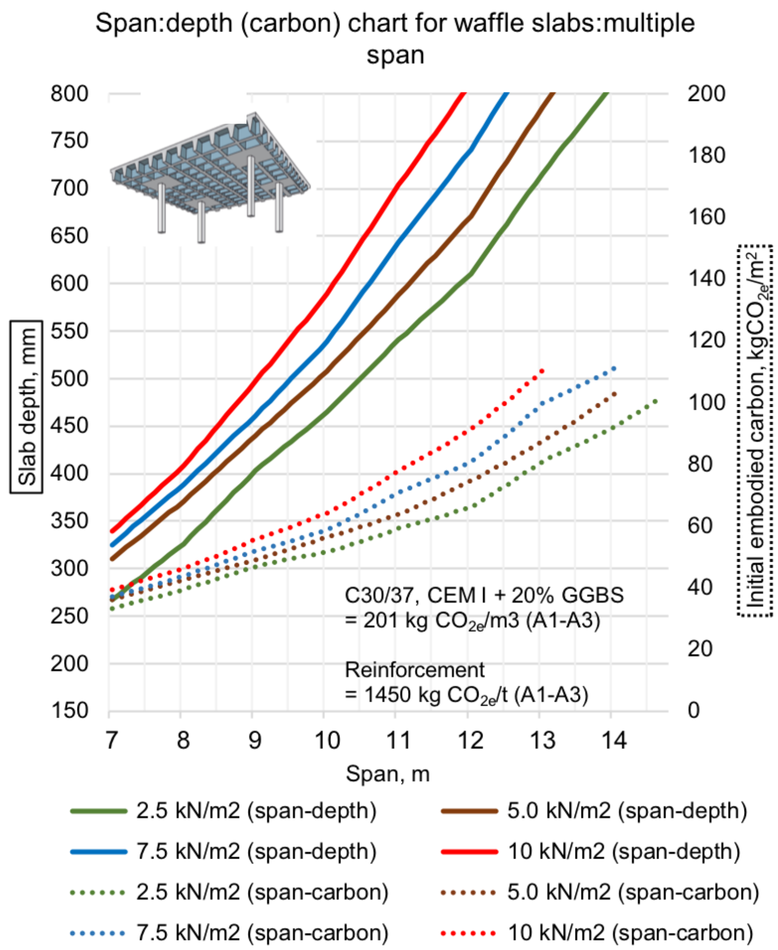


Figure 19 Span:depth and span:slab initial embodied carbon – left, span:depth and span:slab reinforcement – right, waffle slabs – multiple span

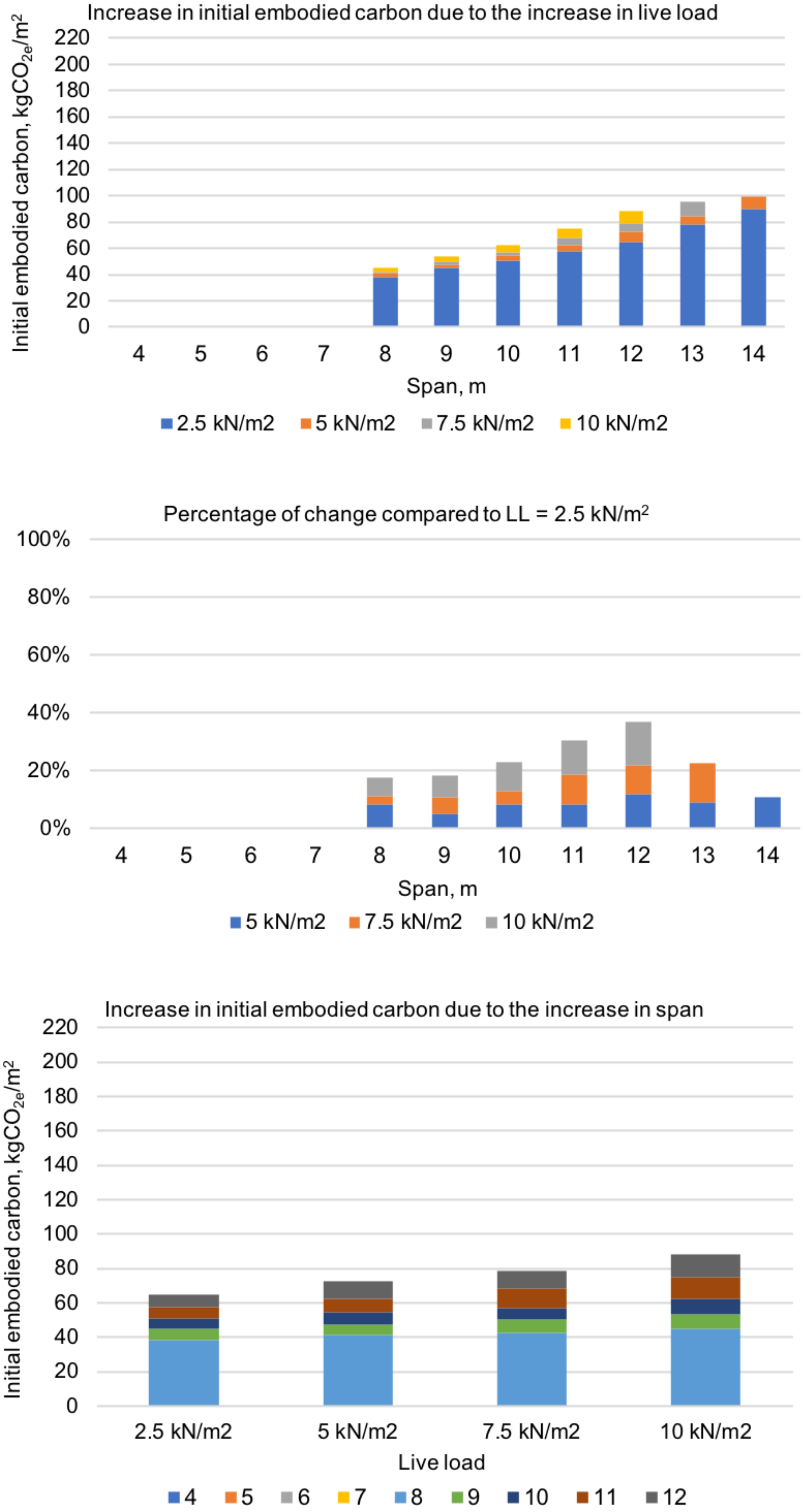


Figure 20 Waffle slabs – increase in initial carbon due to the increase in live load (top), percentage of initial embodied carbon change compared to LL=2.5 kN/m² (middle), increase in initial embodied carbon due to the increase in span (bottom)

4.6. RC slabs type comparison

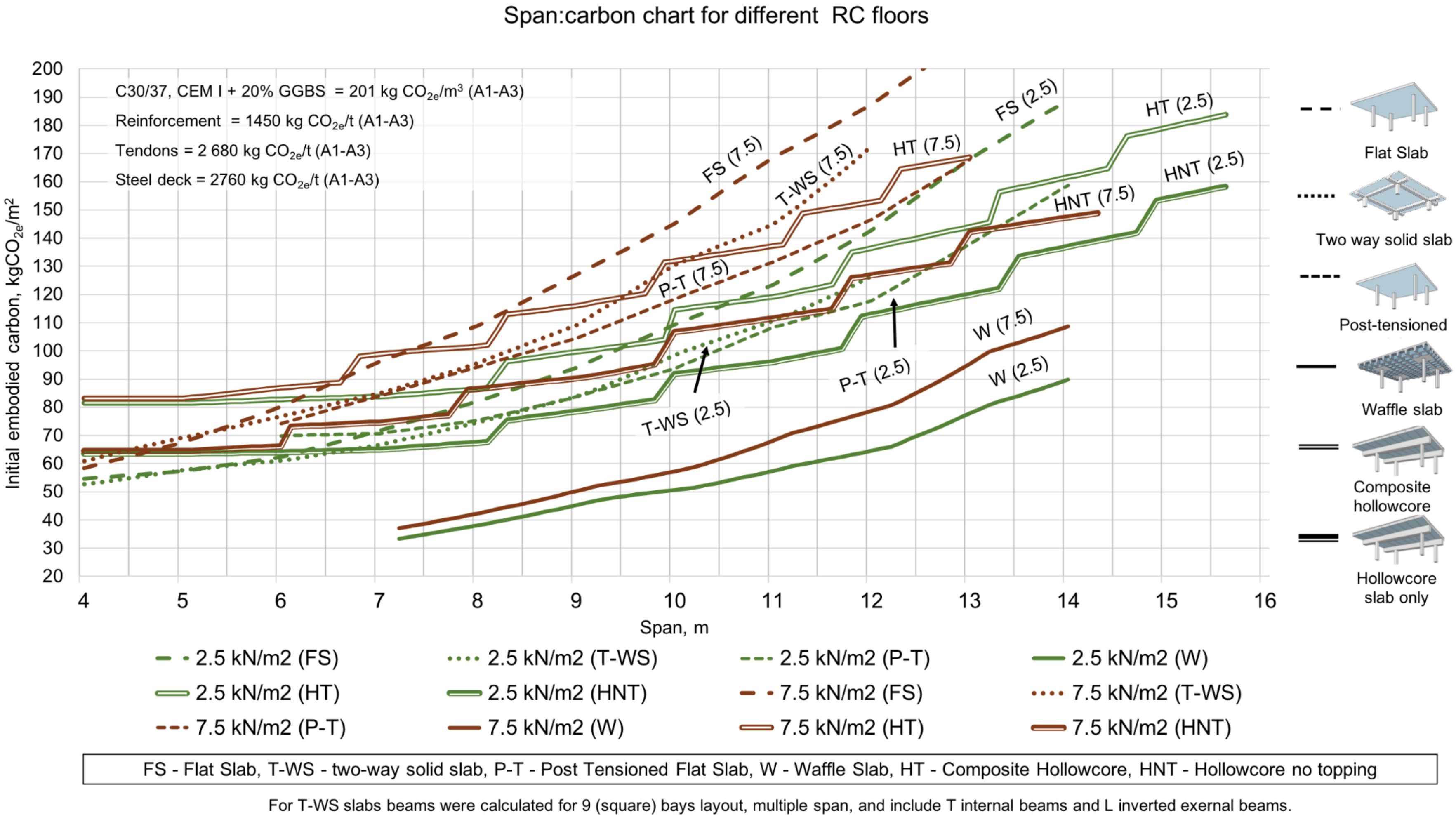
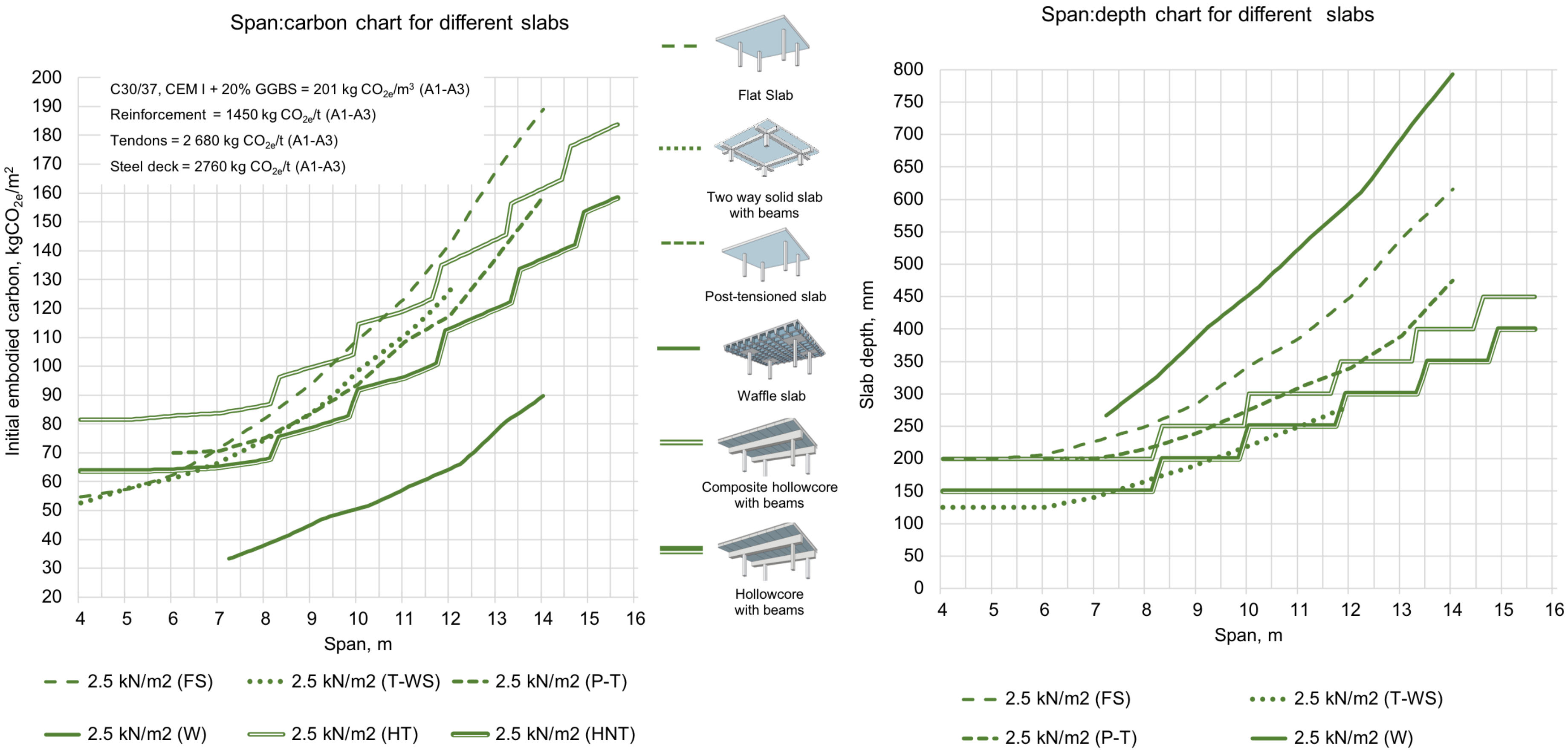


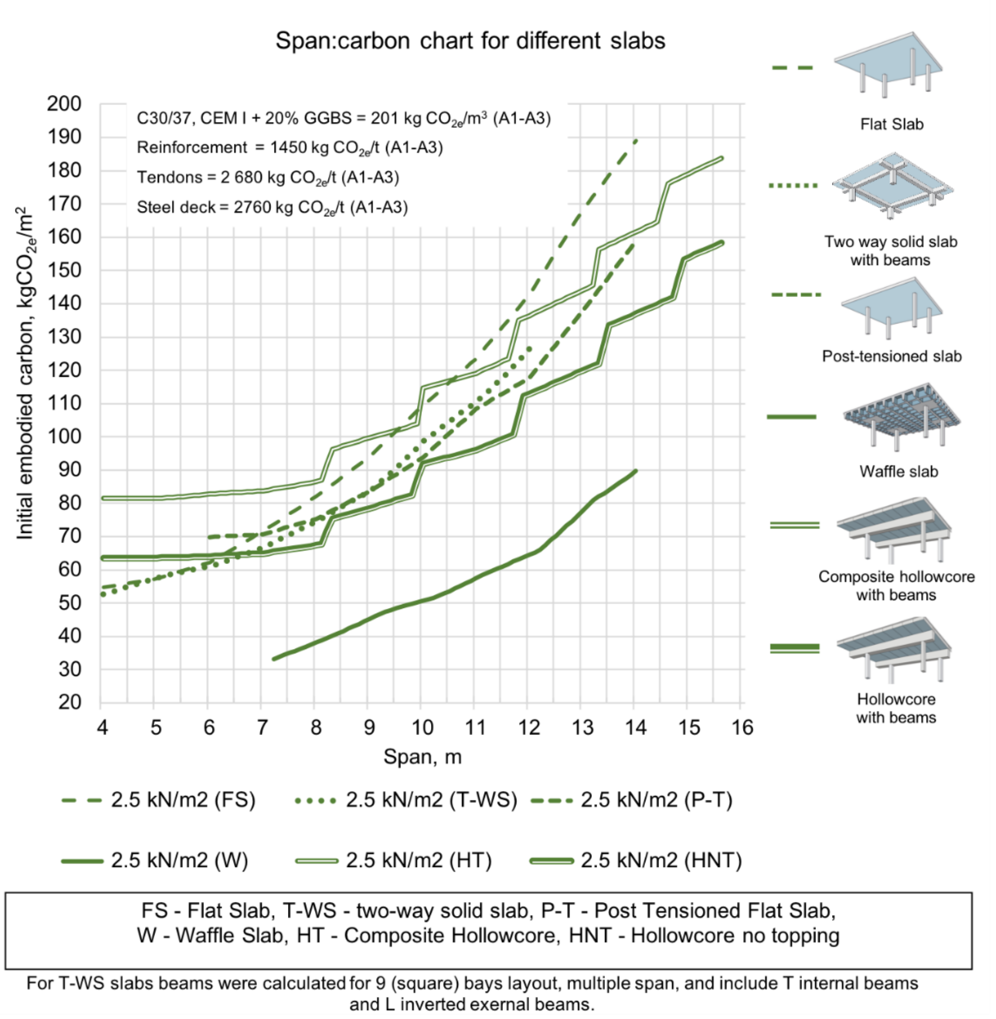
Figure 21 Span:initial embodied carbon - for different RC slabs, live load: 2.5 kN/m² (green), 7.5kN/m² (brown) – multiple span



FS - Flat Slab, T-WS - two-way solid slab, P-T - Post Tensioned Flat Slab,
W - Waffle Slab, HT - Composite Hollowcore, HNT - Hollowcore no topping

For T-WS slabs beams were calculated for 9 (square) bays layout, multiple span, and include T internal beams and L inverted exernal beams.

Figure 22 Span:initial embodied carbon (left) and span:slab depth for different RC slabs, live load: 2.5 kN/m² – multiple span (hollowcore – single span)



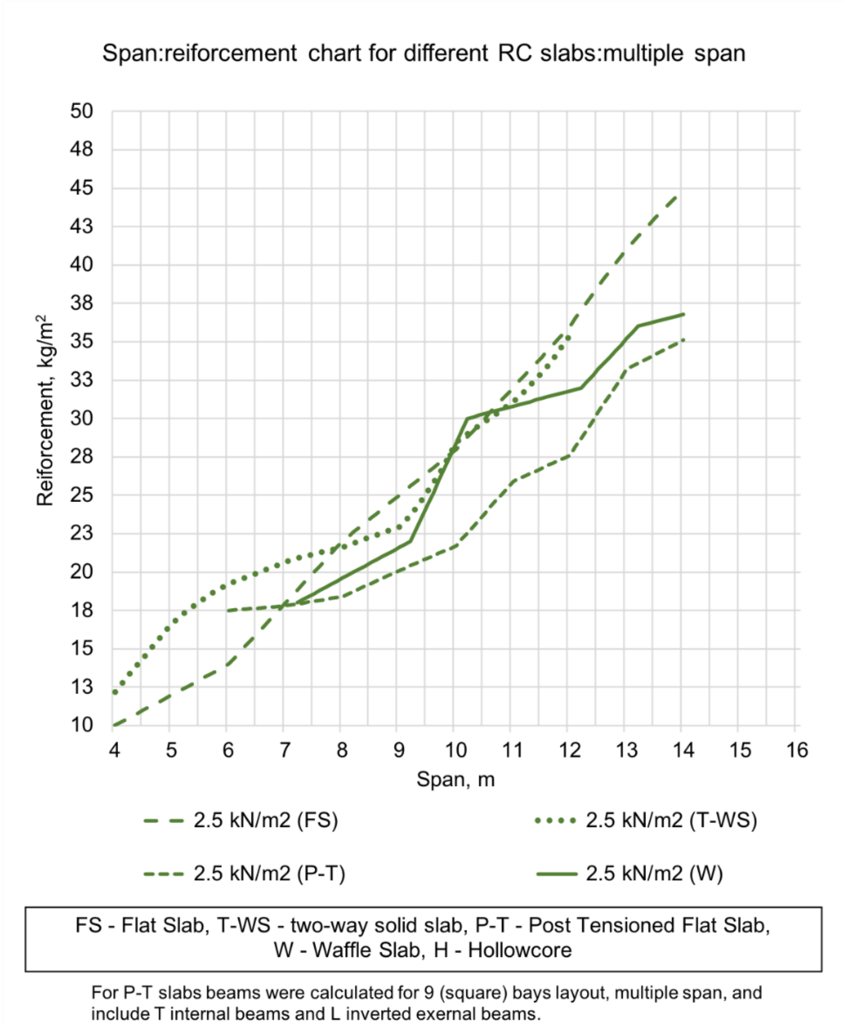
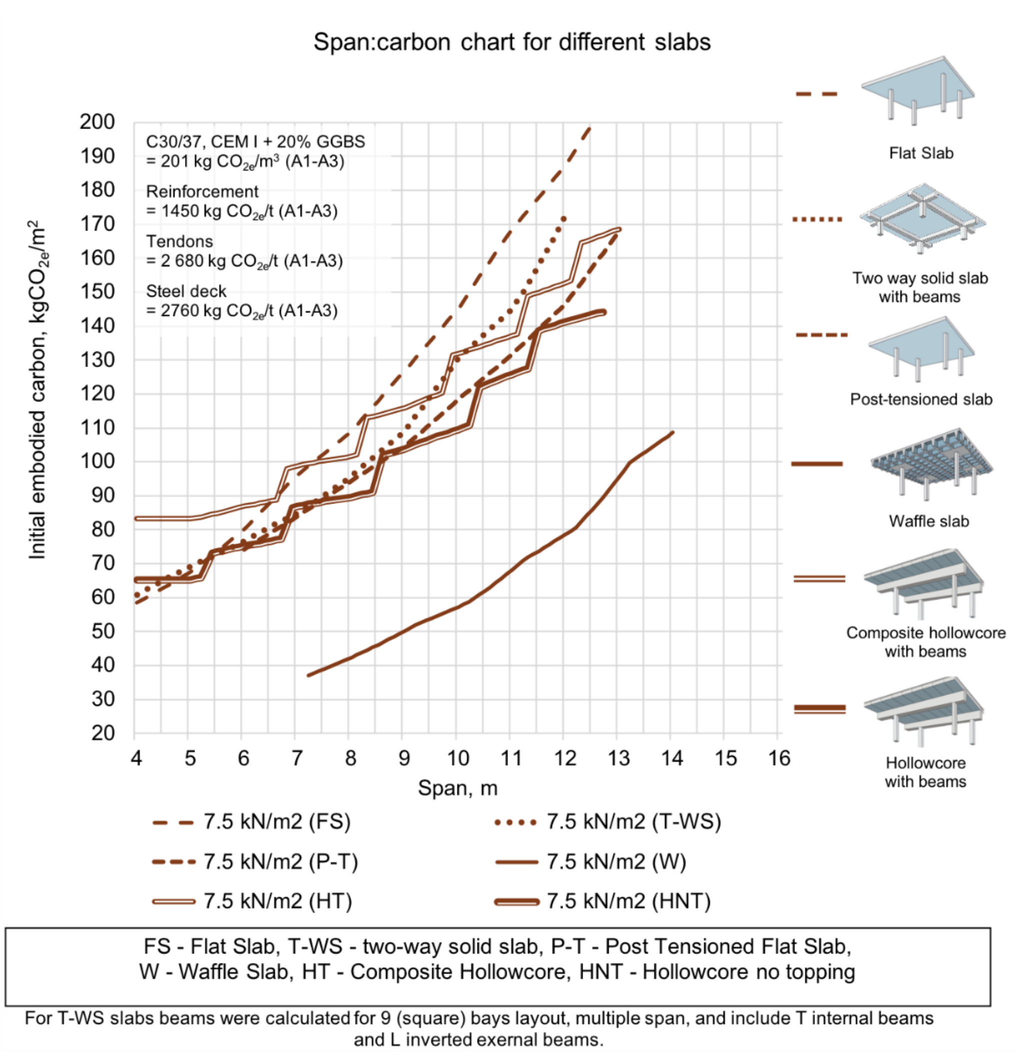


Figure 23 Span:initial embodied carbon (left) and span:reinforcement for different RC slabs, live load: 2.5 kN/m² – multiple span (hollowcore – single span)



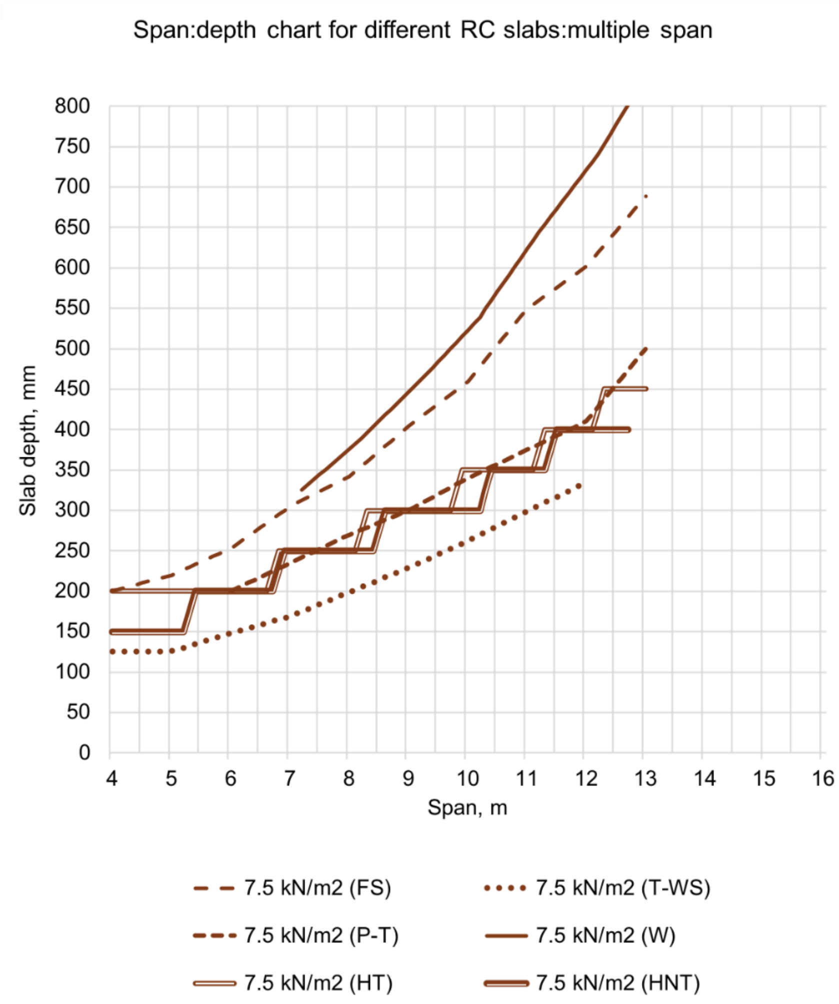
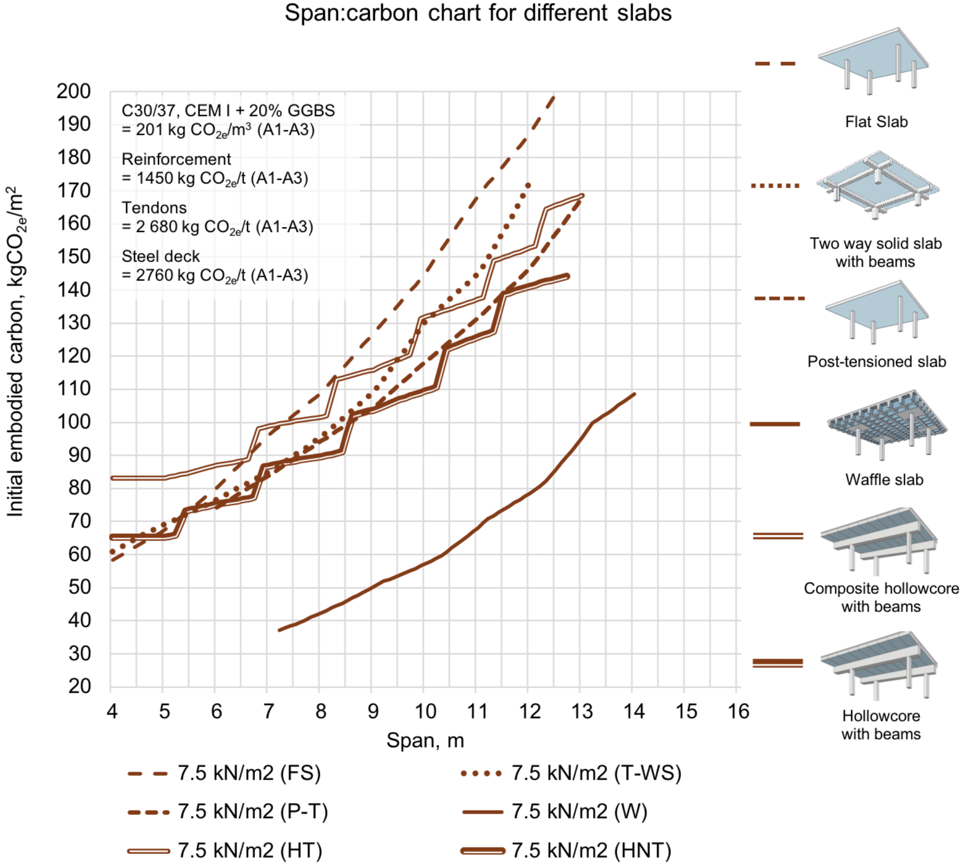
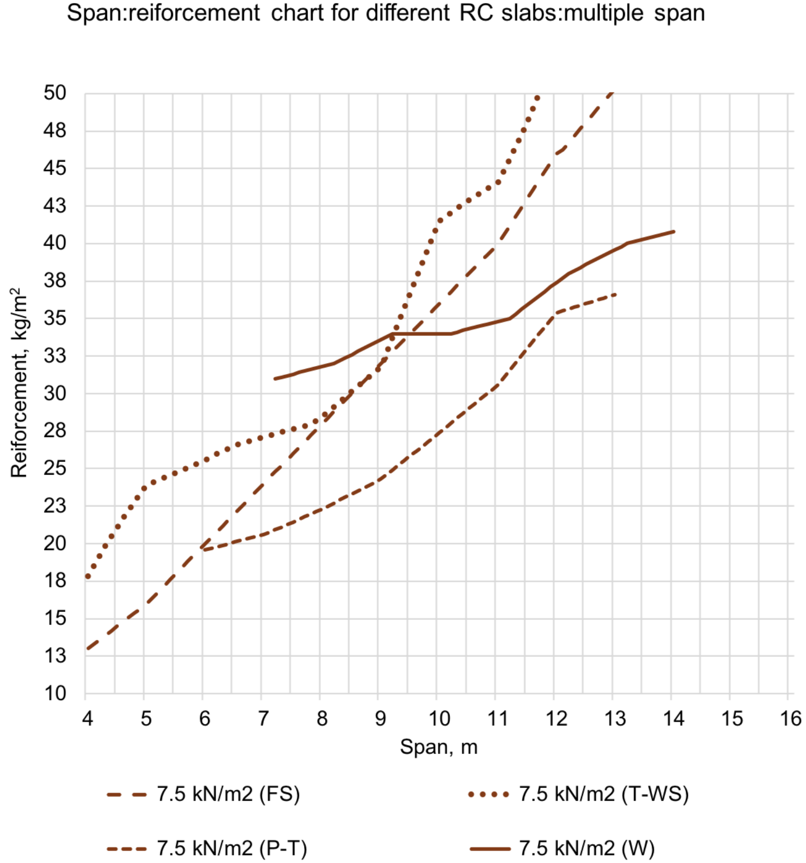


Figure 24 Span:initial embodied carbon (left) and span:slab depth for different RC slabs, live load: 7.5 kN/m² – multiple span (hollowcore – single span)



FS - Flat Slab, T-WS - two-way solid slab, P-T - Post Tensioned Flat Slab,
W - Waffle Slab, HT - Composite Hollowcore, HNT - Hollowcore no topping

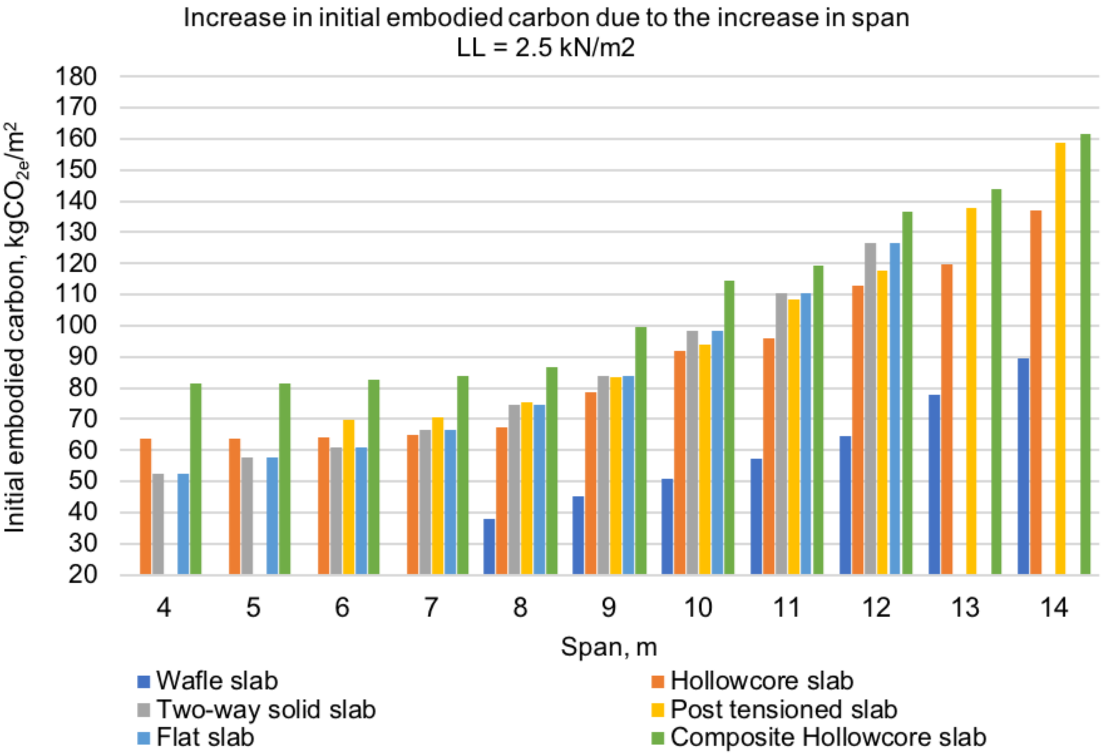
For T-WS slabs beams were calculated for 9 (square) bays layout, multiple span, and include T internal beams and L inverted exernal beams.



FS - Flat Slab, T-WS - two-way solid slab, P-T - Post Tensioned Flat Slab,
W - Waffle Slab, H - Hollowcore

For P-T slabs beams were calculated for 9 (square) bays layout, multiple span, and include T internal beams and L inverted exernal beams.

Figure 25 Span: initial embodied carbon (left) and span:reinforcement for different RC slabs, live load: 7.5 kN/m^2 – multiple span (hollowcore – single span)



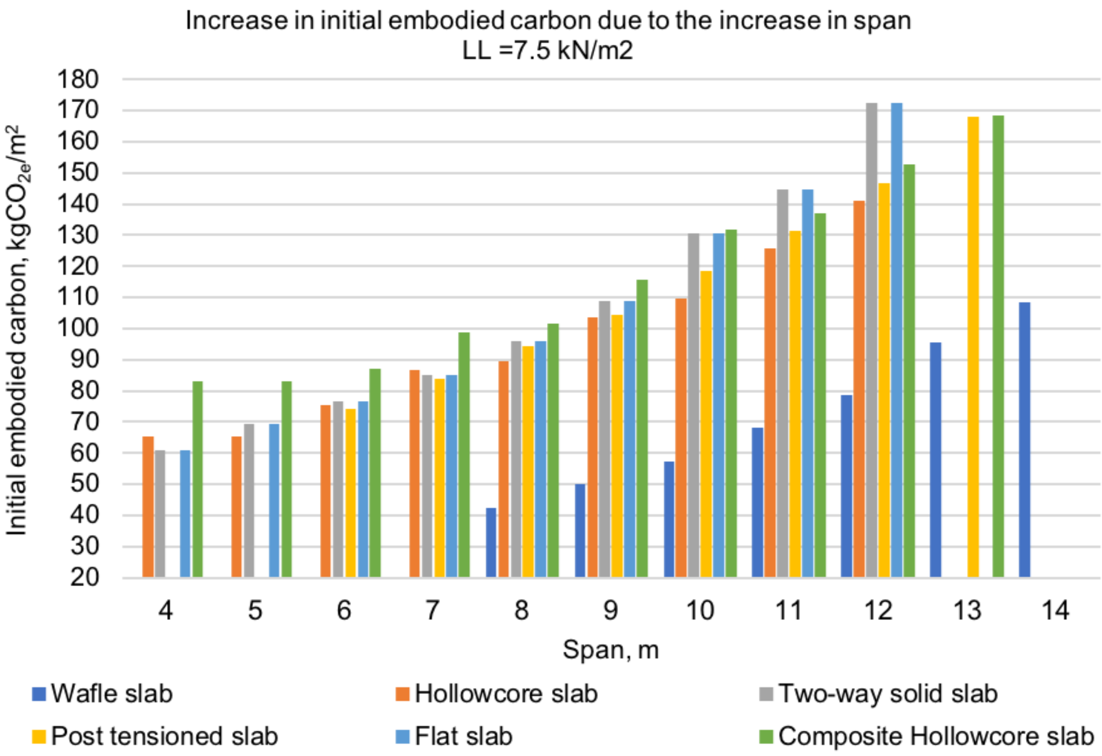


Figure 26 Span:initial embodied carbon for different RC slabs, live load: 2.5 kN/m² (top), 7.5 kN/m² (bottom) – multiple span (hollowcore – single span)

5. Comparison of results with Ramboll case studies (confidential)

(This part of the report is for internal use only and therefore is not included in the published version)

(This part of the report is for internal use only and therefore is not included in the published version)

6. Conclusions

This work presents analysis of different RC floor solutions and an influence of the span and the live loads on initial carbon (cradle-to-gate, Modules A1-A3). Analysis was prepared according to the "Economic Concrete Frame Elements to Eurocode 2" [20] and "How to design concrete structures using Eurocode 2" [21]. A clear relationship was found between the increase in live load and the span (Figure 21). The higher the live load and the longer the span, the greater the value of initial carbon.

For any live loads (2.5, 5.0, 7.5 kN/m^2) and span (7.2 – 14.0 m) waffle slabs was found to be the lowest initial embodied carbon intensive solution (cradle-to-gate, Modules A1-A3), presenting approximately 50% of carbon savings comparing to other solutions (Figure 21). Two way-solid, post tensioned and flat slab was characterised by similar initial carbon intensity for span 4.0 – 7.0 m. For longer span, more than 7m, only two way-solid and post tensioned slabs were comparable. For span longer than 7.0 m flat slab initial embodied carbon increases significantly. Initial embodied carbon for hollowcore slabs (with beams) for a span of more than 7.0 m was found to be lower than for all cases except waffle slab. For a span shorter than 10.0-11.0 m span, composite hollowcore solution (with beams) was characterised by higher initial carbon than flat slabs. For longer span (more than 11.0 m), initial carbon was lower compared to flat slabs.

Increase the live loads from 2.5 to 5.0 kN/m^2 for different span caused increase in initial carbon at the range 2-15% for waffle, post-tensioned and composite hollowcore; and up to 20% for post-tensioned and flat slab (Table 3 – top). A greater impact on initial carbon was found for different span. Table 4 (top) presents the change in the initial embodied carbon for different spans compared to one metre shorter span. Increase in length (from 6.0 to 14.0 m) affects in increase in the initial carbon by 15% for each metre in case of flat slab (e.g. for span 7.0 m it was found 15% of increase in the initial carbon compared to 6.0 m span). The lowest increase in the initial carbon was found for post-tensioned and two-way solid slab and waffle slab. Table 4 (bottom) presents % change in initial carbon for different span and live loads compared to span 4 m and live load 2.5 kN/m^2.

Table 3 Change in the initial embodied carbon for different solutions, % change for higher LL for different span (top), % change for different span compared to span 4m (bottom)

Span m	Flat Slab			Post-Tensioned slab			Two-way solid slab			Hollowcore			Composite Hollowcore			Waffle slab		
	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5
	kN/m2			kN/m2			kN/m2			kN/m2			kN/m2			kN/m2		
4	**54.7**	2%	7%				**52.6**	8%	16%	**63.6**	1%	3%	**81.5**	1%	2%			
5	**57.3**	7%	18%				**57.6**	10%	20%	**63.6**	1%	3%	**81.5**	1%	2%			
6	**62.3**	14%	29%	**69.9**	2%	6%	**61.0**	13%	26%	**64.0**	3%	18%	**82.8**	2%	5%			
7	**71.6**	14%	34%	**70.7**	6%	19%	**66.6**	15%	27%	**64.9**	15%	34%	**83.7**	3%	18%			
8	**82.2**	16%	33%	**75.3**	12%	25%	**74.6**	15%	28%	**67.4**	28%	33%	**86.5**	14%	17%	**38.1**	8%	11%
9	**94.0**	19%	35%	**83.7**	13%	25%	**83.7**	15%	30%	**78.5**	15%	32%	**99.7**	3%	16%	**45.3**	5%	11%
10	**109.2**	22%	33%	**93.8**	11%	26%	**98.5**	18%	32%	**91.8**	16%	19%	**114.6**	3%	15%	**50.7**	8%	13%
11	**123.5**	20%	36%	**108.4**	6%	21%	**110.5**	16%	31%	**96.0**	16%	31%	**119.1**	13%	15%	**57.5**	8%	19%
12	**142.7**	20%	31%	**117.7**	10%	24%	**126.5**	20%	36%	**112.8**	12%	25%	**136.5**	7%	12%	**64.6**	12%	22%
13	**168.0**	11%	26%	**137.8**	6%	22%				**119.9**	19%		**144.0**	9%	17%	**77.8**	9%	23%
14	**189.0**	13%		**158.8**	4%					**136.9**	8%		**161.6**	7%		**89.7**	11%	21%
	kgCO2e/m2	Increase compared to 2.5 kN/m2		kgCO2e/m2	Increase compared to 2.5 kN/m2		kgCO2e/m2	Increase compared to 2.5 kN/m2		kgCO2e/m2	Increase compared to 2.5 kN/m2		kgCO2e/m2	Increase compared to 2.5 kN/m2		kgCO2e/m2	Increase compared to 2.5 kN/m2	

Span m	Flat Slab			Post-Tensioned slab			Two-way solid slab			Hollowcore			Composite Hollowcore			Waffle slab		
	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5
	kN/m2			kN/m2			kN/m2			kN/m2			kN/m2			kN/m2		
4	**54.7**	**55.9**	**58.5**				**52.6**	**56.7**	**60.9**	**63.6**	**64.5**	**65.3**	**81.5**	**82.3**	**83.2**			
5	5%	10%	15%				9%	12%	14%									
6	14%	28%	37%	**69.9**	**71.2**	**74.3**	16%	22%	26%	1%	3%	15%	2%	3%	5%			
7	31%	47%	65%	1%	5%	13%	27%	36%	39%	2%	16%	33%	3%	5%	19%			
8	50%	70%	86%	8%	18%	27%	42%	51%	57%	6%	34%	37%	6%	20%	22%	**38.1**	**41.3**	**42.4**
9	72%	100%	117%	20%	32%	41%	59%	69%	79%	23%	40%	59%	22%	24%	39%	19%	15%	19%
10	100%	138%	148%	34%	46%	59%	87%	105%	114%	44%	65%	68%	41%	44%	59%	33%	33%	35%
11	126%	166%	188%	55%	62%	77%	110%	127%	138%	51%	73%	93%	46%	63%	65%	51%	51%	61%
12	161%	207%	220%	68%	82%	97%	140%	167%	183%	77%	97%	116%	67%	77%	84%	69%	75%	86%
13	207%	233%	262%	97%	104%	126%				88%	120%		77%	91%	103%	104%	105%	125%
14	246%	282%		127%	131%					115%	129%		98%	111%		135%	141%	156%
	Increase compared to span 4 m			Increase compared to span 4 m			Increase compared to span 4 m			Increase compared to span 4 m			Increase compared to span 4 m			Increase compared to span 4 m		

Table 4 Change in the initial embodied carbon for different solutions, % change comparted to previous span (top), % change compared to LL=2.5 kN/m2 and span 4m (bottom).

Span m	Flat Slab			Post-Tensioned slab			Two-way solid slab			Hollowcore			Composite Hollowcore			Waffle slab		
	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5
	kN/m2			kN/m2			kN/m2			kN/m2			kN/m2			kN/m2		
4	0%	0%	0%				0%	0%	0%	0%	0%	0%	0%	0%	0%			
5	5%	10%	15%				9%	12%	14%									
6	9%	16%	19%	0%	0%	0%	6%	9%	11%	1%	3%	15%	2%	3%	5%			
7	15%	15%	20%	1%	5%	13%	9%	11%	11%	2%	16%	33%	3%	5%	19%			
8	15%	16%	13%	7%	13%	12%	12%	12%	13%	5%	31%	19%	4%	16%	17%	0%	0%	0%
9	14%	17%	17%	11%	12%	11%	12%	12%	14%	21%	21%	19%	19%	18%	17%	19%	15%	19%
10	16%	19%	14%	12%	10%	13%	18%	21%	20%	36%	23%	22%	32%	20%	30%	12%	15%	14%
11	13%	12%	16%	16%	11%	11%	12%	11%	11%	22%	24%	21%	20%	31%	18%	13%	13%	19%
12	16%	16%	11%	9%	12%	11%	14%	18%	19%	23%	19%	29%	19%	23%	16%	12%	16%	15%
13	18%	8%	13%	17%	12%	15%				25%	27%		21%	17%	23%	20%	17%	21%
14	12%	15%		15%	13%					21%	16%		18%	19%		15%	17%	14%
	Increase compared to previous result			Increase compared to previous result			Increase compared to previous result			Increase compared to previous result			Increase compared to previous result			Increase compared to previous result		

Span m	Flat Slab			Post-Tensioned slab			Two-way solid slab			Hollowcore			Composite Hollowcore			Waffle slab		
	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5	2.5	5.0	7.5
	kN/m2			kN/m2			kN/m2			kN/m2			kN/m2			kN/m2		
4	**54.7**	2%	7%				**52.6**	8%	16%	**63.6**	1%	1%	**81.5**	1%	2%			
5	5%	12%	23%				9%	20%	32%		1%	1%		1%	2%			
6	14%	30%	47%	**69.9**	2%	6%	16%	31%	46%	1%	4%	4%	2%	4%	7%			
7	31%	50%	76%	1%	7%	20%	27%	46%	61%	2%	17%	17%	3%	6%	21%			
8	50%	74%	99%	8%	20%	35%	42%	63%	82%	6%	36%	36%	6%	21%	25%	**38.1**	8%	11%
9	72%	104%	132%	20%	35%	50%	59%	82%	107%	23%	42%	42%	22%	25%	42%	19%	25%	32%
10	100%	143%	165%	34%	49%	69%	87%	120%	148%	44%	68%	68%	41%	45%	62%	33%	44%	50%
11	126%	171%	208%	55%	65%	88%	110%	145%	175%	51%	75%	75%	46%	65%	68%	51%	63%	79%
12	161%	214%	242%	68%	86%	110%	140%	188%	228%	77%	99%	99%	67%	79%	87%	69%	90%	106%
13	207%	240%	287%	97%	108%	140%				88%	123%	123%	77%	93%	107%	104%	122%	150%
14	246%	290%		127%	135%					115%	132%	132%	98%	113%		135%	160%	185%
	Increase compared to 2.5 kN/m2 and span 4 m			Increase compared to 2.5 kN/m2 and span 4 m			Increase compared to 2.5 kN/m2 and span 4 m			Increase compared to 2.5 kN/m2 and span 4 m			Increase compared to 2.5 kN/m2 and span 4 m			Increase compared to 2.5 kN/m2 and span 4 m		

7. Summary and future work

This report presents correlation between initial embodied carbon (cradle-to-gate), span and impact of the live load for 5 different reinforced concrete (RC) floor solutions. Comparison was made between flat slabs, two-way solid slab (both with and without beams), post-tensioned slabs, composite hollowcore with 50 mm structural topping (both with and without beams), hollowcore without structural topping (both with and without beams) and waffle slabs. Calculation were based on material quantities included in "Economic Concrete Frame Elements to Eurocode 2" [20] and "How to design concrete structures using Eurocode 2" [21].

To allow the comparison between different structural systems, fixed concrete mixed were assumed. This approach is a simplification because the miminum slab thickness is not always the solutions to get the lowest initial embodied carbon per m^2. Nevertheless, this analysis presents the differences between the commonly used reinforced concrete solutions to allow for early design decisions such as span, live loads and type of slab solution.

Main assumptions limit the deflection to span/250 limiting span-to-depth ratio, and do not assess of the theoretical deflection calculated according to Eurocode. Therefore, material utilisation of structural elements (UR) and the influence of serviceability limits (SLS) on initial embodied carbon was not included in this report and will be at the scope of future research as well as analysis of composite floor solutions.

This report can be used as a design guidance for early design stage to find relationships between different RC floor solutions, span and initial (cradle-to-gate) embodied carbon.

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RESOURCE EFFICIENCY
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