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How does conceptual design impact the cost and carbon footprint of structures?

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ABSTRACT

Making sustainable conceptual design decisions is the key to reduce the environmental impact of the construction industry. Such early decisions, which must be given in a short timeframe, have the largest impact on a project's quality, cost and embodied carbon. This study showed how much the conceptual design decisions affect the cost and carbon footprint of a building's structure using our Non-dominated Sorted Genetic Algorithm II tool. First, we tested the tool's reliability by comparing its solutions with three case studies from literature. Then, we showed that by quickly examining various conceptual design solutions on a Pareto graph (which spotlights cost and CO_2-optimized options), more sustainable design alternatives can be identified. Then, using the tool, we analyzed 36 building configurations, providing a spectrum of embodied carbon emissions (including the life cycle assessment steps A1, A2, A3, A4, A5, C2, C3, C4) ranging between 60 and 360 $kgCO_2e/m^2$. By comparing 25 material types from 15 databases (EPDs and ICE), we concluded that the geometry decisions (span length, height and shape) have the largest influence, material type (steel, timber, reinforced concrete), recycling and reuse of steel are crucial, and the embodied carbon calculations are highly sensitive to the supplier data and location. Overall, this study showed that architects and engineers possess the ability to significantly reduce the embodied carbon of structural systems by selecting the appropriate materials and structural system at the conceptual design stage.

1. Introduction

The construction sector accounted for 36 % of total energy use and 37 % of embodied CO_2 in 2020 [1], 10 % of which resulted from manufacturing building materials and products such as steel and concrete. The international agreements [2–6] require countries to reduce their greenhouse gas (GHG) emissions, and the structural engineers hold the key here. A crucial step for structural engineers to minimise embodied carbon and costs is to carefully choose the proper materials and use them effectively in the building's structural system. The conceptual design phase has the largest impact on a project's quality, cost and embodied carbon (Fig. 1), covering up to 80 % of the resources involved in the project [7,8]. In meeting the global CO_2 emission objectives worldwide [1,9,5], the early decisions of a project regarding the choice of structural materials, span lengths, building shape, and building height become fundamental. In this context, multi-objective design optimisation becomes a key method.

Valuable studies exist about multi-objective optimisation of structural frames [11–14]. Park and Grierson [15] proposed a multi-criteria optimum conceptual design of building structural layouts under specified requirements using a computational procedure. Miles et al. [16] developed a multi-criteria optimisation tool for commercial buildings using a weighted approach to calculate their clear span, costs, and embodied CO_2. Kanyilmaz, Tichell, and Loiacono [17,18] developed a conceptual building design tool for reinforced concrete and steel structures using NSGA-II to minimise construction costs, increase free space and lower the embodied CO_2. Khodadadi [19] represented several design options for a mid-rise residential complex in terms of structural performance, heating energy consumption, shell cost, and environmental and life cycle impact. Yazdi et al. [20] researched the best load-bearing spanning design options with the least amount of product and manufacturing waste. Thai et al. [21] studied multi-objective optimisation of CLT-reinforced concrete composite floor using the NSGA-II in terms of overall weight, total thickness, and final cost. In recent years, researchers have created tools [22–28] that offer various combinations in response to the typical requirement for statistically exploring and

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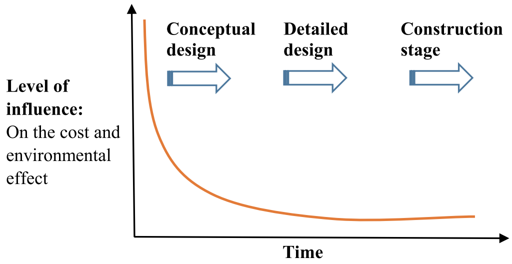


Fig. 1. Degree of influence on design versus project running time [10].

visualising the design space for conceptual design. However, these studies focus on specific types of structures or materials, such as reinforced concrete, steel or cross-laminated timber, and a holistic approach is still missing that can consider multiple design objectives and constraints simultaneously. Hence, the trade-off between different conceptual design decisions regarding costs and embodied carbon is still not clear. Construction industry would benefit from a sensitivity analysis comparing the effects of conceptual design decisions on embodied cost and carbon emissions.

The current need for multi-objective design and sensitivity analysis is driven by the pressing issue of climate change, and the requirements to reduce the carbon footprint of structures [29,30]. Clark [31] showed a wide range of results between 300 and 1650 kg CO_2e/m^2 from case

Table 1
Typical number of floors for each type of stability system, extracted from [6].

	Steel	RC.	Mass timber
Moment-resisting frames	1–4	1–2	1–2
Braced frames	1–20	–	1–4
RC shear walls/RC cores	4–20	2–20	4–18

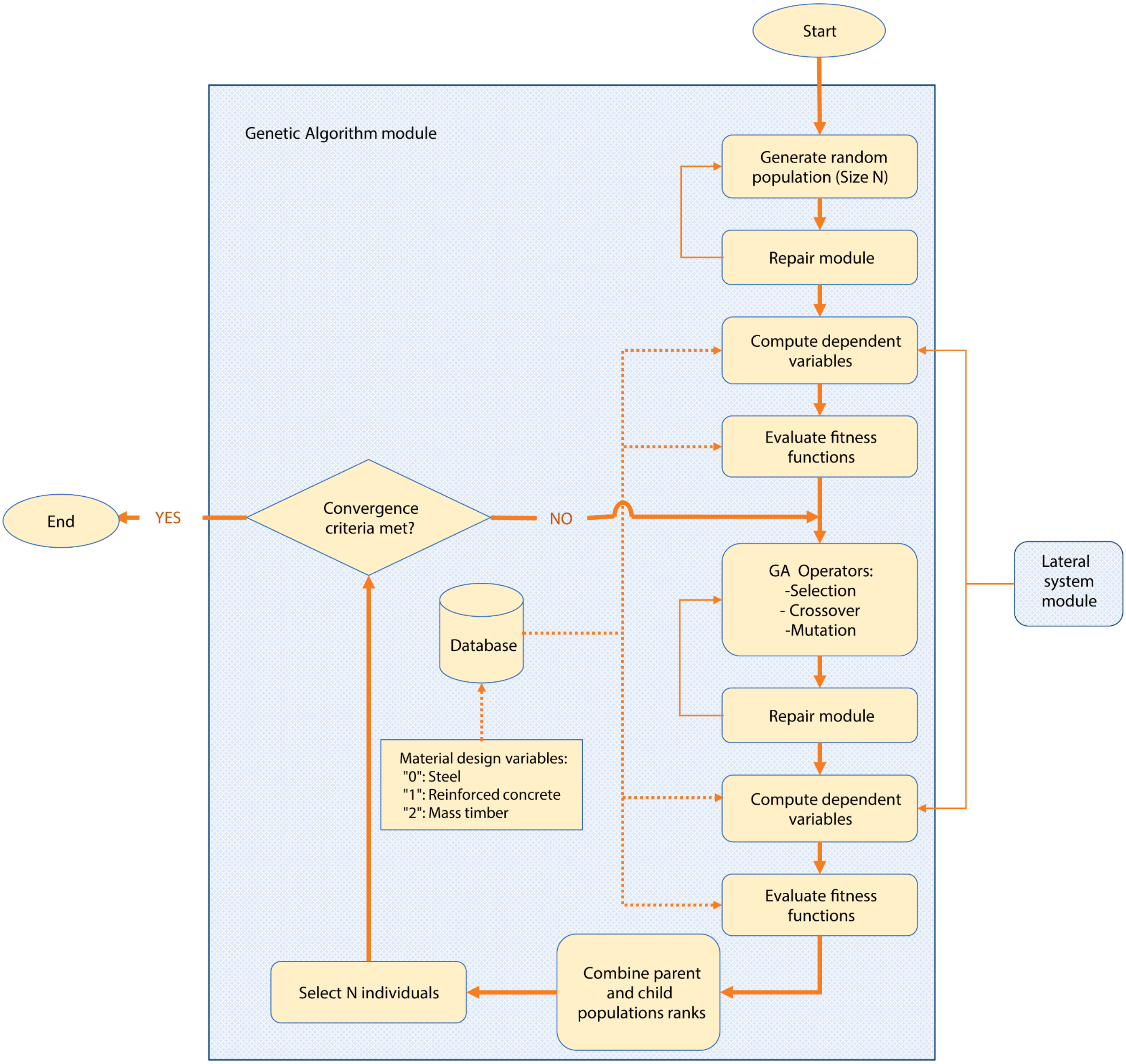


Fig. 2. Basic algorithm workflow [18].

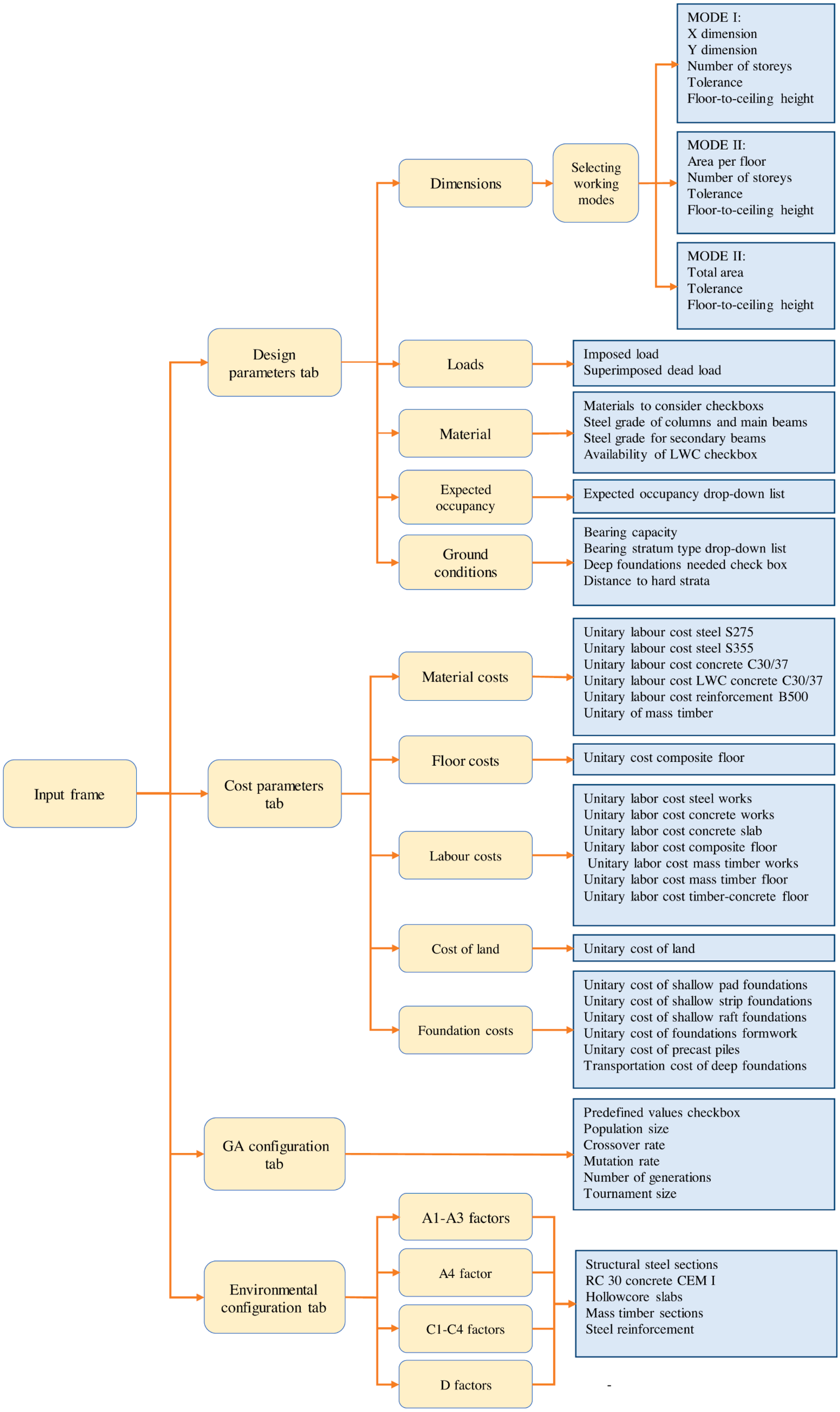


Fig. 3. The main structure of the inputs frame. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

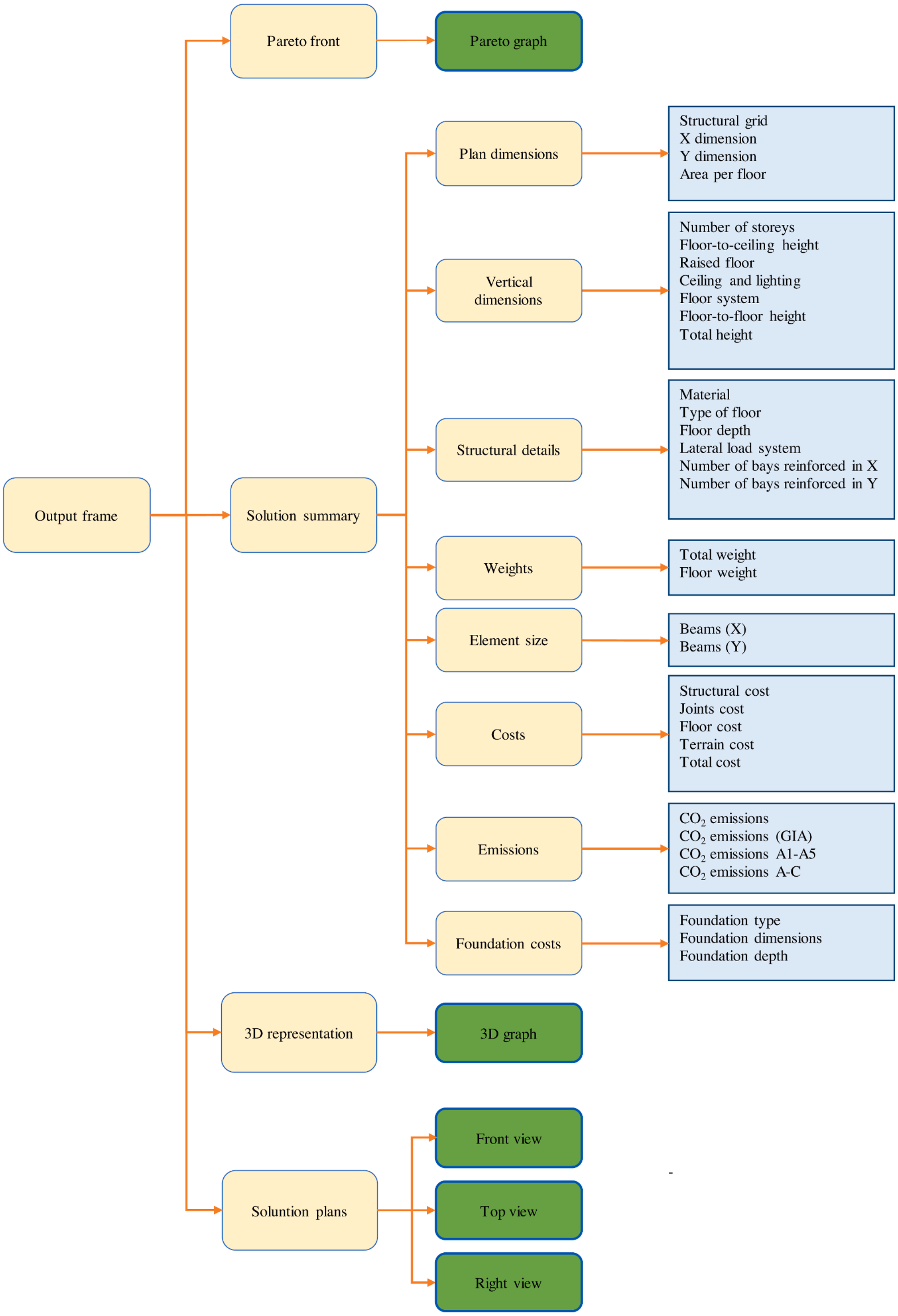


Fig. 4. The main structure of the outputs frame. Graphs are represented in green, and variables are in blue.

studies of office buildings provided by numerous companies. De Wolf et al. [29] pointed out that engineers still lack benchmarking for embodied CO_2 in buildings. Dani et al. [32] conducted a detailed Life Cycle Assessment (LCA) to quantify and compare the amount of embodied carbon for two buildings in New Zealand, one made of light timber and the other of lightweight steel. Chen [33] conducted a study to evaluate the embodied CO_2 of RC and timber buildings. Helal et al. [34] compared LCA of different structural systems and materials for tall buildings concerning various load types (imposed, façade, lateral, static, and dynamic). Hawkins et al. [35] used dynamic LCA to assess the greenhouse gas emissions of different building materials (concrete, steel, and timber) for a medium-rise building structure. Gauch et al. [36]

Table 2
Unitary material and labour costs for steel and RC (from the year 2020) [37].

	Steel S275	Steel S355	Reinforced concrete 30/37	Lightweight Reinforced Concrete	Reinforcing steel B500	Mass timber
Material cost (umc)	0.86 €/kg	0.96 €/kg	82.65 €/m3	107.44 €/m3	0.81 €/kg	500€/m^3
Labour cost (ulc)	0.42 €/kg		200 €/m3		–	60€/m^3

Table 3
Unitary material and labour costs for different floor systems of steel and RC (from the year 2020) [37].

	Decking Composite floor	Precast RC slab					Reinforced concrete slab
		100	150	200	250	260	
Material cost (umc, €/m^2)	41.85	34.08	36.78	40.98	50.58	51.28	*
Labour cost (ulc, €/m^2)	28.7	17.69	17.69	18.75	19.8	19.8	35

Table 4
Unitary material and labour costs for different floor systems of mass timber (from the year 2020).

	CLT floors	CLT-reinforced concrete composite slab
Material cost (umc, €/m2)	*	*
Labour cost (ulc, €/m2)**	10	22.5

**Labour cost is assumed to be cheaper than RC one [38].

explored how design and operation parameters affect embodied carbon, construction cost, and heating/cooling loads in multi-storey buildings. While there is consensus between industry and academia regarding the urgency to tackle the challenges of climate change, significant progress is still needed in comprehensively understanding the impact of conceptual design decisions on embodied cost and carbon emissions across various building and material types.

In this article, we conducted a sensitivity analysis to compare the effects of different conceptual design decisions on the cost and embodied carbon of structures made of steel, timber, and reinforced concrete (which account for most of the construction market share worldwide). The results of this analysis provide valuable insights for architects, engineers, and builders, who can use this information to make more informed decisions during the early design stages of a building project, ultimately leading to more sustainable and cost-effective structures.

2. Methodology

The sensitivity analysis has been performed using a multi-objective conceptual design tool based on NSGA II, created in 2020 by Kanyilmaz et al. [17,18]. Fig. 2 describes the algorithm workflow of the tool describing the iterative process and the convergence criteria. The model consists of a genetic algorithm (GA) engine including the material selection, the floor system, grid size, building dimension selections, and a

Table 5
A1-A3 carbon (No.1-No.6) and waste factors (kg CO_2e/kg) are extracted from [8]. From EPDs, A1-A3 is used [44].

No	Product	Database	WF	A1-A3	A4	A5	C2-C4
1.	Structural steel “typical”, global average	ICE	0.01	1.550	0.005	0.0175	0.018
2.	RC30 reinforced concrete CEM I, 0 % GGBS		0.053	0.129	0.005	0.0081	0.018
3.	Hollow core slab, precast		0.01	0.166	0.032	0.0022	0.018
4.	Mass timber sections, CLT		0.01	0.437	0.032	0.0050	0.027
5.	Mass timber sections, CLT, no sequestration		0.01	0.437	0.032	0.0214	1.667
6.	Steel reinforcement, global average		0.053	1.990	0.005	0.1161	0.018
7.	Reused structural steel sections (EMR Group)	EPD	0.01	0.0466	0.005	0.0025	0.018
8.	Recycled structural steel sections, EA furnace (Beltrame SPA)		0.01	0.3693	0.005	0.0057	0.018
9.	C28/35 CIIIB ready mix concrete, 12 % GGBS (Hanson UK)		0.053	0.0696	0.005	0.0049	0.018
10.	Structural steel, 87 % post-consumer steel (BE Group)		0.01	0.719	0.005	0.0092	0.018
11.	Structural steel, 70 % EAF, 82 % post, pre-consumer (Bauforumstahl)		0.01	1.130	0.005	0.0251	0.018
12.	Concrete ready mix, CEM II, 0 % GGBS (Heracles)		0.01	0.100	0.005	0.0012	0.018
13.	Concrete ready mix CEM III, 40 % recycled cement (Lafargeholcim)		0.01	0.118	0.005	0.0014	0.018
14.	Mass timber sections, GLT (Zaza Timber)		0.01	0.526	0.032	0.0059	0.027
15.	Mass timber sections TGLT (Abodo Wood)		0.01	0.603	0.032	0.0066	0.027

Table 6
Incompatibilities between materials and floor systems.

Steel	R.C.	Mass timber	
✓	×	×	Composite beams
✓	×	×	Cellular composite beams
✓	✓	×	CLT-reinforced concrete composite slab (for steel frames)
×	✓	×	CLT slab (for steel frames)
×	✓	×	Precast reinforced concrete units.
×	✓	×	One-way reinforced concrete slab
×	✓	×	Two-way reinforced concrete slab
×	✓	×	Flat reinforced concrete slab
×	×	✓	CLT-reinforced concrete composite slab
×	×	✓	Mass timber ribbed slab
×	×	✓	One-way CLT slab
×	×	✓	Two-way CLT slab
×	×	✓	Flat CLT slab

Table 7
Compatibilities between floor systems and span lengths (m) [17,18,57–59].

Span (m)	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13	13.5	14	14.5	15	15.5	16	16.5	17	17.5	18
Composite beams	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Cellular composite beams	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
CLT-RC composite slab, for steel	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																				
CLT slab (for steel frames)	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																				
Precast reinforced concrete units	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																
One-way RC slab	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
Two-way RC slab	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
Flat reinforced concrete slab	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
CLT-RC composite slab	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																				
Mass timber ribbed slab	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																		
One-way CLT slab	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																				
Two-way CLT slab	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																				
Flat CLT slab	▨	▨	▨	▨	▨	▨	▨	▨	▨																						

Table 8
Inputs used to model the restrictions of the six-storey office building.

X dimension	36 *m*	Superimposed dead load	1.5 kN/m^2
Y dimension	36 *m*	Materials considered	Steel, RC, mass timber
Number of storeys	6	Steel grade secondary	S275
Tolerance	0 %	Steel grade primary	S355
Floor-to-ceiling height	3 *m*	LWC availability	NO
Imposed load	5 kN/m^2	Occupancy	Office
		Soil bearing capacity	250kN/m^2

lateral load-resisting system (LLRS) module that determines the best LLRS to use, sizes and locates it in the building floor plan. To begin with, a random parent population of size N is generated, where each parent solution represents a potential conceptual design for a building. Each created parent solution is defined by a specific combination of design variables. These design variables serve as inputs for the genetic algorithm and encompass various conceptual design decisions, such as material selection, grid and structural layouts, and the floor system. The fitness function calculation step comprises the “cost”, “span”, and “embodied carbon” evaluation sub-steps. New individuals from previous populations are created by using GA operators (Selection, Crossover, Mutation) and Repair modules to eliminate some unfeasible and conflicted options. The termination condition of GA is defined when a program run will stop. The aim of termination criteria is to obtain the optimal solutions that meet the convergence stops. In this GA module, the termination conditions occur when a certain number of generations (predefined by users) is reached. The detailed information about the tool and its GA methodology can be read in our previous article [18].

The conceptual (preliminary) sizing rules used in the tool have been explained in detail in our previous work (Kanyilmaz et al. [17,18]). Three lateral resisting systems have been considered: moment-resisting

Table 10
Inputs used to model the restrictions of the nine-storey office building.

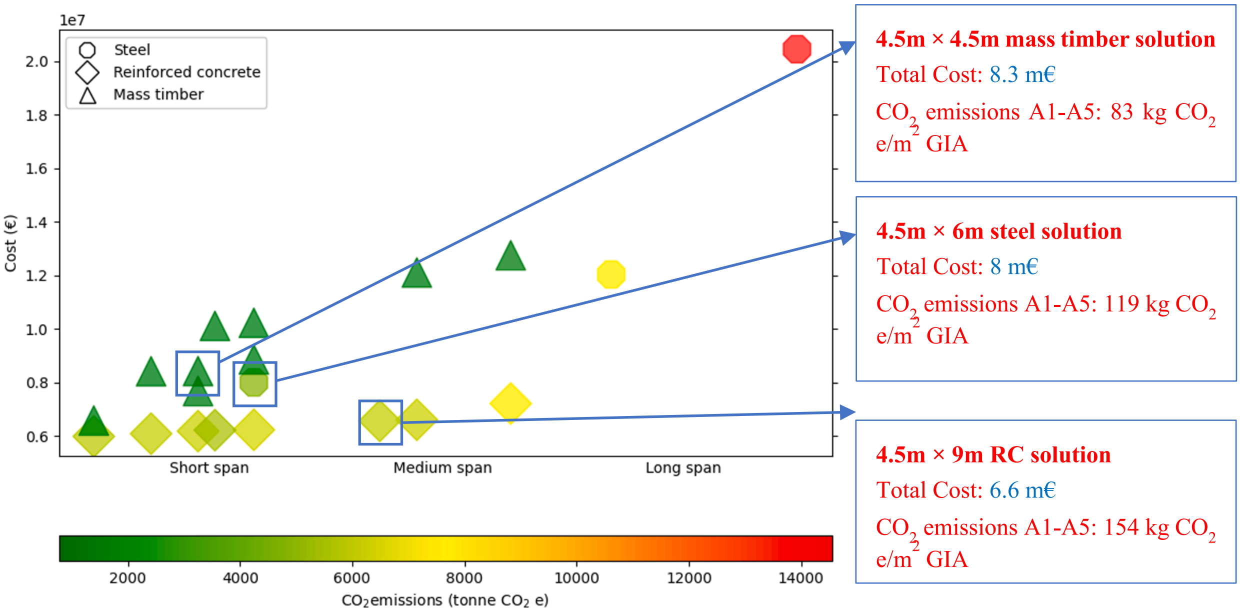
X dimension	81 *m*	Superimposed dead load	1.5 kN/m^2
Y dimension	54 *m*	Materials considered	Steel, RC, mass timber
Number of storeys	9	Steel grade secondary	S275
Tolerance	0 %	Steel grade primary	S355
Floor-to-ceiling height	2.7 *m*	LWC availability	NO
Imposed load	2.5 kN/m^2	Occupancy	Office
		Foundation	Deep foundation

Table 9
Comparison between benchmarks and the equivalent tool solutions for each material.

	Reinforced concrete		**Steel**		**Mass timber**	
	Benchmark	**Our tool**	**Benchmark**	**Our tool**	**Benchmark**	**Our tool**
Total building dimension (m)	36 × 36	36 × 36	36 × 36	36 × 36	36 × 36	36 × 36
Structural grid (m)	9 × 9	9 × 9	9 × 9	9 × 9	9 × 9	9 × 9
Number of storeys	6	6	6	6	6	6
Type of floor	Flat slab	Flat slab	Composite slab	Composite slab	Mass timber ribbed slab	Mass timber ribbed slab
Floor depth (mm)	400	400	120	130	100	100
Secondary beams (mm)	NA	NA	533UB × 82	533UB × 82	NA	320 × 800
Primary beams (mm)	NA	NA	686UB125	686UB125	NA	360 × 1000
Columns (mm)	700 × 700	700 × 700	356UC235	356UC235	480 × 1000	480 × 1000
Lateral load resisting system	RC cores shear walls	RC cores	RC cores braced steel bays	RC cores	RC cores and braced steel bays	RC cores
Foundation type	Pad shallow foundations	Pad shallow foundations	Pad shallow foundations	Pad shallow foundations	Pad shallow foundations	Pad shallow foundations
Foundation dimension (m) Width × Length × Thickness	2.8 (only thickness provided)	5.6 × 5.6 × 2.8	2.8 (only thickness provided)	5.6 × 5.6 × 2.8	2.3 (only thickness provided)	4.6 × 4.6 × 2.3
Total cost (m€)	N.A	1.75	N.A	2.33	N.A	2.32
Embodied CO_2 A1-A3 ($kgCO_2e/m^2$ GIA)	331	331	227	220	142	134

Table 11
Comparison: original solution (a), the tool equivalent solution (b), and the tool alternative solutions (c, d, and e).

	a) Design example from literature	**b) The tool's approach [Equivalent solution]**	**c) The tool's approach [Steel optimised solution]**	**d) The tool's approach [RC optimised solution]**	**e) The tool's approach [Mass timber optimised solution]**
Total building dimension:	81 m × 54 *m*	81 m × 54 *m*	81 m × 54 *m*	81 m × 54 *m*	81 m × 54 *m*
Structural grid:	6 m × 9 *m*	6 m × 9 *m*	4.5 m × 6 *m*	4.5 m × 9 *m*	4.5 m × 4.5 *m*
Type of floor:	Precast reinforced concrete slab	Precast reinforced concrete slab	Decking composite slab	Two-way concrete slab	Two-way timber slab
Floor depth:	150 mm	250 mm	130 mm	125 mm	160 mm
Secondary beams:	NA	IPE240	IPE270	300 mm × 380 mm	160 mm × 360 mm
Primary beams:	NA	IPE450	IPE300	300 mm × 750 mm	160 mm × 360 mm
Columns:	NA	HEA360	HEA260	460 mm × 460 mm	400 mm × 400 mm
Lateral load resisting system:	Reinforced concrete core	Reinforced concrete core	Reinforced concrete core	Reinforced concrete core	Reinforced concrete core
Foundation details	N.A	1 precast pile per group, D = 27.5 cm, Q = 75 tonnes	1 precast pile per group, D = 27.5 cm, Q = 75 tonnes	1 precast pile per group, D = 27.5 cm, Q = 75 tonnes	1 precast pile per group, D = 27.5 cm, Q = 75 tonnes
Total cost:	NA	6.80 m€	8.00 m€	6.57 m€	8.26 m€
Embodied CO_2 A1-A5	405 $kgCO_2e/m^2$ GIA	393 $kgCO_2e/m^2$ GIA	119 $kgCO_2e/m^2$ GIA	154 $kgCO_2e/m^2$ GIA	83 $kgCO_2e/m^2$ GIA
Embodied CO_2 A + C	410 $kgCO_2e/m^2$ GIA	425 $kgCO_2e/m^2$ GIA	126 $kgCO_2e/m^2$ GIA	166 $kgCO_2e/m^2$ GIA	89 $kgCO_2e/m^2$ GIA



4.5m × 4.5m mass timber solution
Total Cost: 8.3 m€
CO_2 emissions A1-A5: 83 kg CO_2 e/m^2 GIA

4.5m × 6m steel solution
Total Cost: 8 m€
CO_2 emissions A1-A5: 119 kg CO_2 e/m^2 GIA

4.5m × 9m RC solution
Total Cost: 6.6 m€
CO_2 emissions A1-A5: 154 kg CO_2 e/m^2 GIA

Fig. 5. Pareto front, 9-storey office building.

Table 12
Inputs used to model the restrictions of the three-storey office building.

X dimension	42 *m*	Superimposed dead load	2.1 kN/m^2
Y dimension	42.5 *m*	Materials considered	Steel
Number of storeys	3	Steel grade secondary	S275
Tolerance	0 %	Steel grade primary	S355
Floor-to-ceiling height	3 *m*	LWC availability	NO
Imposed load	3.8 kN/m^2	Occupancy	Office

frames, braced frames, and shear walls (perimeter walls and concrete cores). Moment-resisting frames and reinforced concrete cores are selected as suitable for all material types. On the other hand, bracing systems are selected suitable with steel frames and mass timber frames. Typical number of floors for each lateral system are decided according to Norman et al. [6] as shown in Table 1. Figs. 3 and 4 show the main structures of the calculation tool.

2.1. Cost calculations

In the construction market, costs can vary daily due to factors imposed by suppliers, transportation, and material availability. Therefore, for this calculation, the default unit cost is fixed based on data from 2020, mainly from the sources [37–40].

Cost of the structure: evaluates the building's structural systems, such as columns, beams, and lateral load-resisting systems. It takes into consideration both the material and labour costs. Both have been directly proportional to the quantity of material. The below formula may be used to compute it:

$$C_{structure} = W_{material} \bullet (umc_{material} + ulc_{material}) \tag{1}$$

Where $umc_{material}$ is the unitary material cost and $ulc_{material}$ is the unitary labour cost. The values for the parameters of steel and RC are specified in Table 2.

Although CLT market prices vary depending on product size, larger companies use an average price of 500€/m^3 [41]. The labour cost of mass timber is taken as 30 % of the RC [38,39].

Table 13
Comparison: Original solution (a), the tool equivalent solution (b), and the tool alternative solutions (c, d, and e).

	a) Design example from the company	b) The tool's approach [Equivalent solution]	c) The tool's approach [Steel optimised solution]	d) The tool's approach [RC optimised solution]	e) The tool's approach [Mass timber optimised solution]
Total building dimension:	42 m × 42.5 *m*	42 m × 42.5 *m*	42.5 m × 42 *m*	42.5 m × 42.5 *m*	42.5 m × 42 *m*
Structural grid:	6 m × 8.5 *m*	6 m × 8.5 *m*	7 m × 8.5 *m*	7 m × 8.5 *m*	6 m × 8.5 *m*
Type of floor:	CLT-RC composite slab	CLT-RC composite slab	Decking composite slab	Two-way RC slab	Mass timber ribbed slab
Floor depth:	335 mm	335 mm	130 mm	183 mm	320 mm
Secondary beams:	W18 × 86 (USA)	IPE450 (EU, similar)	IPE450	300 mm × 590 mm	160 mm × 360 mm
Primary beams:	W18 × 86 (USA)	IPE450 (EU, similar)	IPE550	300 mm × 710 mm	320 mm × 680 mm
Columns:	HSS8.625X0.322 (USA)	HEA220 (EU, similar)	HEA260	410 mm × 410 mm	400 mm × 400 mm
Lateral load resisting system:	Braced frame	Braced frame	Braced frame	RC core	Braced frame
Foundation type	Strip shallow foundations	Pad shallow foundations	Pad shallow foundations	Pad shallow foundations	Pad shallow foundations
Foundation dimension (w × l × t) (m)	3 × 0.75 (w × t)	2.2 × 2.2 × 1.1	2.2 × 2.2 × 1.1	2.7 × 2.7 × 1.4	1.8 × 1.8 × 0.9
Total cost:	NA	2.25 m€	1.76 m€	1.43 m€	2.05 m€
Embodied CO_2 A1-A5	NA	167 $kgCO_2e/m^2$ GIA	141 $kgCO_2e/m^2$ GIA	184 $kgCO_2e/m^2$ GIA	68 $kgCO_2e/m^2$ GIA
Embodied CO_2 A + C	NA	178 $kgCO_2e/m^2$ GIA	149 $kgCO_2e/m^2$ GIA	200 $kgCO_2e/m^2$ GIA	72 $kgCO_2e/m^2$ GIA

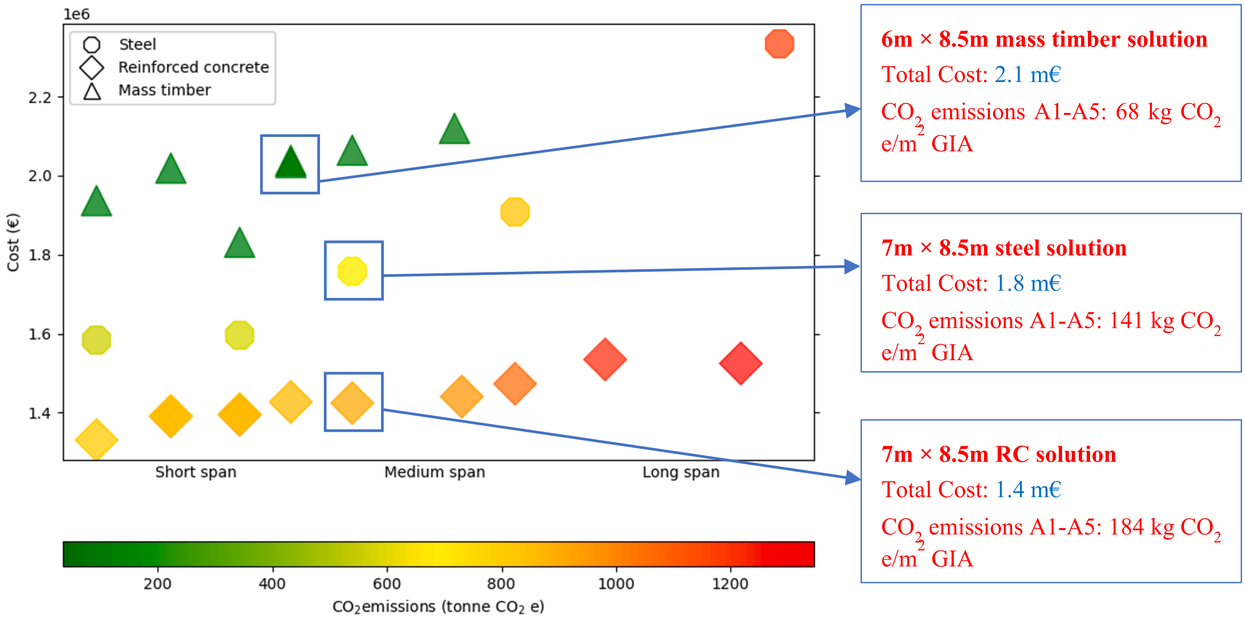


Fig. 6. Pareto front, 3-storey office building.

Cost of joints: This cost is especially relevant in steel structures, and it differs depending on the beam-to-column connection type. Bolts are typically adopted for pinned joints, whereas welded connections are used to create fixed joints. Even if the material cost difference between the two connections is not significant, welding is a more expensive operation usually involving inspection. The cost of the joints is considered as a proportion of the structure's total cost. As proposed by [40], the profile cost is increased by 20 % in case of pinned connections, and 60 % in case of fixed connections. The cost percentage increase for fixed joints is determined as follows:

$$Percentage = \frac{Fixed\ joints}{Total\ joints} = \frac{2\bullet(X_{NLLS}+Y_{NLLS})}{X_{NBAY}\bullet(Y_{NBAY}+1)+Y_{NBAY}\bullet(X_{NBAY}+1)} \quad (2)$$

The total connection cost is calculated as follows:

$$C_{joints} = C_{material}\bullet(percentage\bullet upc_{fixed}+(1-percentage)\bullet upc_{pinned}) \quad (3)$$

Where the unitary percentual cost of fixed joints is $upc_{fixed} = 0.6$ and the unitary percentage cost of pinned joints $upc_{fixed} = 0.2$. For timber joints, the joint cost is computed as the procedure of steel joints for the sake of simplicity.

Cost of floors: Measured by the total slab area and the unitary floor cost per quadratic meter:

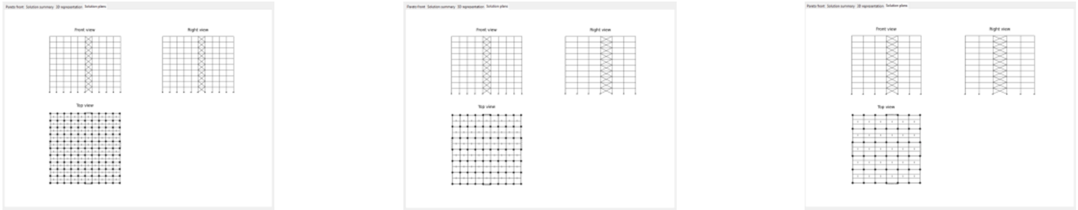
$$C_{floor} = X_{RDIM}\bullet Y_{RDIM}\bullet NS\bullet(umc_{floor}+ulc_{floor}) \quad (4)$$

Where umc_{floor} is the unitary material cost of the slabs with a unit in €/m^2 and ulc_{floor} is the unitary labour cost. The labour costs represent the necessary workforce and equipment for each type (Table 3).

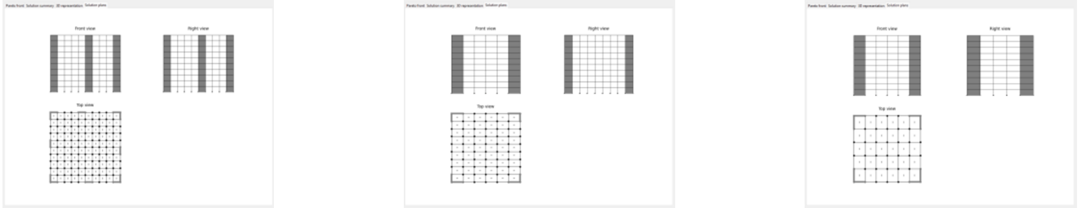
For reinforced concrete slabs ("*" in Table 3), the material cost per square meter (€/m^2) depends on the slab's thickness and the steel reinforcement weight. It is calculated using the unitary reinforced concrete and steel reinforcement costs in Table 4.

$$umc_{concrete\ slab} = S_D\bullet umc_{concrete}+S_R\bullet umc_{steel} \quad (5)$$

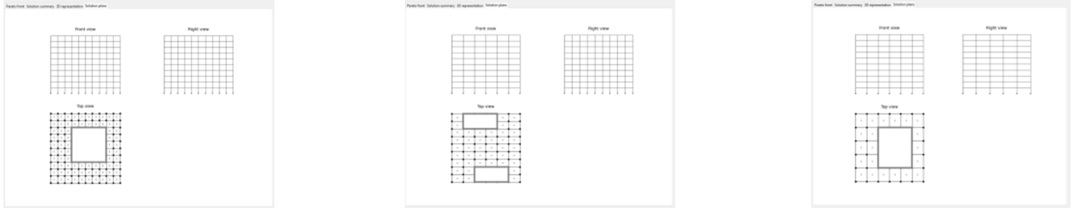
For CLT and CLT-RC composite slabs ("*" in Table 4), the material cost



4.5m×4.5m (steel) 5m×7.5m (steel) 7.5m×9m (steel)



4.5m×4.5m (RC) 5m×7.5m (RC) 7.5m×9m (RC)



4.5m×4.5m (mass timber) 5m×7.5m (mass timber) 7.5m×9m (mass timber)

Fig. 7. Output plan views.

Table 14
Input parameters.

X dimension	45 *m*	Slab type-steel frame	RC composite slab
Y dimension	45 *m*	Slab type-RC frame	One/two way slab
Number of storeys	10	Slab type-timber frame	CLT ribbed slab
Floor-to-ceiling height	2.5 *m*	LLRS type-steel frame	Steel bracing
Imposed load	2.5 kN/m^2	LLRS type-RC frame	RC shear wall
Superimposed dead load	1.5 kN/m^2	LLRS type-timber frame	Concrete core
Steel grade secondary	S275		
Steel grade primary	S275		
Occupancy	Residential		
Soil bearing capacity	50kN/m^2		

per square meter (€/m^2) depends on the slab thickness. In the case of the CLT-RC composite slab, 50 mm of concrete topping with its steel reinforcement is considered, calculated using the unitary reinforced concrete and mass timber costs (Tables 3 and 4).

$$umc_{CLT\ slabs} = S_D \bullet umc_{mass\ timber} \tag{6}$$

$$umc_{CLT-RC\ composite\ slab} = S_{D(CLT)}{}^{*} \bullet umc_{mass\ timber} + 0.05^{*} \bullet umc_{concrete} \tag{7}$$

$^*S_{D(CLT)}$ is the thickness of the CLT slab, and 0.05 is the 50 mm thickness of the concrete topping

The total cost (C) is estimated by summing all of the individual costs:

$$C = C_{land} + C_{structure} + C_{joints} + C_{foundation} + C_{floor} + C_{lateral\ system} \tag{8}$$

2.2. Embodied carbon calculations

The principle of the embodied carbon calculation is to multiply the quantity of each material by a carbon factor for the life cycle modules under consideration [8,42] as shown in the Eq. (9).

$$Material\ quantity\ (kg) \times carbon\ factor\ (kgCO_2e/kg) = embodied\ carbon\ (kgCO_2e) \tag{9}$$

In our study, life cycle analysis (LCA) is used to assess embodied carbon [43], considering life cycle modules A1-A5 (raw material supply, transport, manufacturing regarding the product, transport and construction installation regarding the construction process) and, C (end-of-life). Carbon factors of modules (A1-A4) and (C2-C4) are extracted from 15 different sources including EPDs, ICE database and literature [8], as shown in Table 5. The carbon factor of module A5 is calculated by the tool using the following equation [8]:

$$ECF_{A5w} = WF \times (ECF_{A13} + ECF_{A4} + ECF_{C2} + ECF_{C34}) \tag{10}$$

Where:

ECF_{A5w} = Construction waste embodied carbon factor of module A5.

ECF_{C2} = Transportation away from the site of module C2.

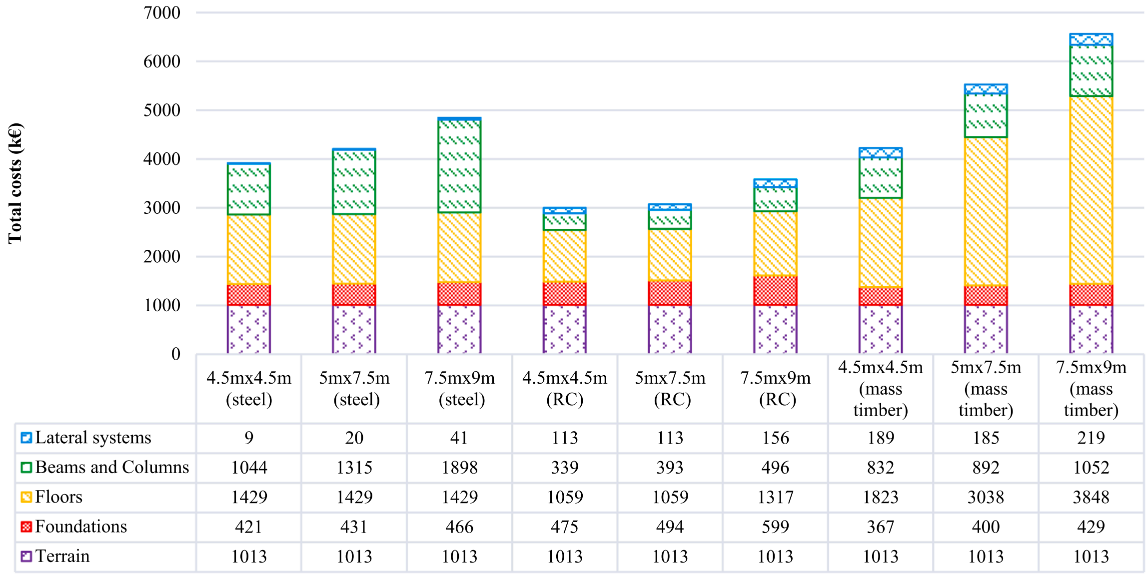
ECF_{C34} = Waste processing and disposal emissions associated with construction waste material module C3-C4.

ECF_{A13} = Carbon factors of module A1-A3.

WF = Waste factor of the material shown in Table 5.

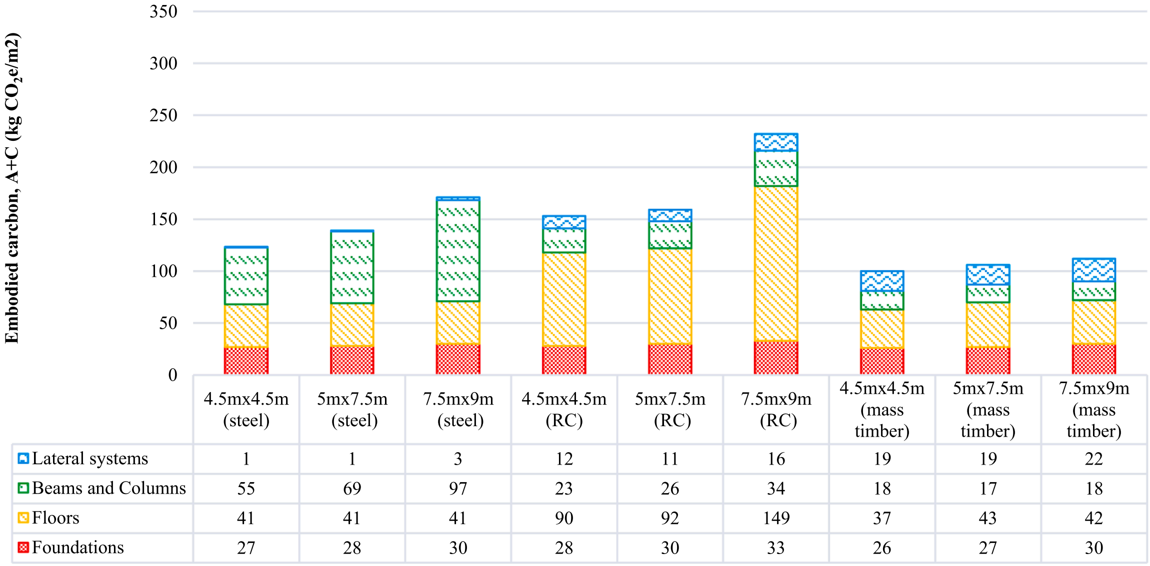
RC30 reinforced concrete CEM I considers no recycled aggregate or cement replacement. RC beams and columns are assumed to contain 2 % reinforcement (of the concrete volume), while RC foundations and precast piles are assumed to contain 1 % reinforcement (of the concrete volume). While this assumption can provide a standard conceptual reinforcement value, it is important to note that a more refined calculation of the reinforcement quantity can impact significantly the calculated embodied carbon values, showing the importance of early design decisions. C28/35 CIIIB ready mix concrete consists 12 % of Ground granulated blast furnace slag (GGBS) (Hanson UK [45]). Concrete ready mix (Heracles [46]) does not contain GGBS. Concrete ready mix (Lafargeholcim Spain [47]) contains 40 % recycled cement.

Reused steel sections come from demolished/deconstructed structures or those fabricated but not erected (EMR [48]). Recycled steel sections are hot rolled structural profiles produced with Electric Arc Furnace (EAF) starting from post and pre consumer steel scraps (S235, S275, S355) (Beltrame SPA [49]). Structural steel sections (BE Group



	4.5mx4.5m (steel)	5mx7.5m (steel)	7.5mx9m (steel)	4.5mx4.5m (RC)	5mx7.5m (RC)	7.5mx9m (RC)	4.5mx4.5m (mass timber)	5mx7.5m (mass timber)	7.5mx9m (mass timber)
▨ Lateral systems	9	20	41	113	113	156	189	185	219
▨ Beams and Columns	1044	1315	1898	339	393	496	832	892	1052
▨ Floors	1429	1429	1429	1059	1059	1317	1823	3038	3848
▨ Foundations	421	431	466	475	494	599	367	400	429
▨ Terrain	1013	1013	1013	1013	1013	1013	1013	1013	1013

Fig. 8. Total cost comparison between different span lengths.



	4.5mx4.5m (steel)	5mx7.5m (steel)	7.5mx9m (steel)	4.5mx4.5m (RC)	5mx7.5m (RC)	7.5mx9m (RC)	4.5mx4.5m (mass timber)	5mx7.5m (mass timber)	7.5mx9m (mass timber)
▨ Lateral systems	1	1	3	12	11	16	19	19	22
▨ Beams and Columns	55	69	97	23	26	34	18	17	18
▨ Floors	41	41	41	90	92	149	37	43	42
▨ Foundations	27	28	30	28	30	33	26	27	30

Fig. 9. Embodied carbon emissions (kg CO_2e/m^2) between different span lengths.

[50]) are produced with 87 % post-consumer raw material and in a site with fossil-free electricity, waste comping from steel scrap. Structural steel sections (Bauforumstahl [51]) are produced using 70 % EAF and 30 % Basic Oxygen Furnace with 82 % pre and post-consumer raw material.

In case of mass timber, the effect of biogenic carbon (sequestration) has been analysed using different C2-C4 values taken from ICE database. When evaluating the influence of biogenic carbon uptake and release, two basic methodologies may be recognised in traditional LCAs used for buildings [52]. The first strategy, often known as the “0/0 approach” or “carbon neutral strategy,” relies on the idea that a bio-based product’s release of CO_2 at the end of its useful life is equalled by an equivalent intake of CO_2 during the growth of biomass. The second one, known as the “-1/+1” strategy, entails monitoring all biogenic carbon fluxes over the course of a building’s existence. This method takes into account both the absorption (−1) and release (+1) of biogenic CO_2 as well as the transfers of biogenic carbon among the various systems. In this article, the latter approach is applied since it provides an overview of all biogenic carbon flows. However, these methods do not consider emissions from harvesting the importance of which is recently highlighted by Peng et al. (2023) [53]. As a result, the timber’s embodied carbon emissions, as presented in the paper, may be underestimated. Mass timber sections (Zaza Timber [54]) are glued laminated timber (GLT) elements from spruce and pine (94.5 % wood), while Mass timber sections (Abodo Wood [55]) are made of thermally modified glued laminated timber (TGLT).

The coefficients for A4 are used for locally-supplied steel and concrete, and nationally-supplied timber (the assumptions are that the timber would come to the site within the country while concrete and steel producers can be found in the locations relatively close to the construction site, and there are much less mass timber facilities compared to steel and concrete ones [56]).

Table 15
Input parameters.

X dimension	45 *m*	Slab type-steel frame	RC composite slab
Y dimension	45 *m*	Slab type-RC frame	One/two way or flat slab
Number of storeys	4/6/8	Slab type-timber frame	CLT ribbed slab
Span length	7.5 m × 7.5 *m*	LLRS type-steel frame	Steel bracing
Floor-to-ceiling height	2.5 *m*	LLRS type-RC frame	RC shear wall
Imposed load	2.5 kN/m^2	LLRS type-timber frame	Timber bracing/ Concrete core
Superimposed dead load	1.5 kN/m^2		
Steel grade secondary	S275		
Steel grade primary	S275		
Occupancy	Residential		
Soil bearing capacity	50kN/m^2		

The structure's embodied carbon is estimated as follows:

$$E_{structure} = W_s \bullet e_s + W_c \bullet e_c + W_t \bullet e_t + W_{fdn} \bullet e_c \tag{11}$$

$$W_c = V_c \bullet \delta_{concrete}; W_t = V_t \bullet \delta_{masstimber} \tag{12}$$

$$W_{fdn} = V_{fdn} \bullet \delta_{concrete} \tag{13}$$

Where V_{fdn} is the volume of the reinforced concrete foundation systems in cubic meters, e_s, e_c, and e_t are the total embodied carbon factors for steel, RC and mass timber, respectively. The total weight of reinforced concrete in kg is computed from the slab load to determine the embodied CO_2 created by the floor type (S_L).

$$E_{floor} = W_f \bullet e_f \tag{14}$$

$$W_f = \frac{(S_L \bullet X_{RDIM} \bullet Y_{RDIM} \bullet NS) \bullet 1000}{9.81} \tag{15}$$

The following equation considers embodied CO_2 from steel reinforcement of RC floors, beams, columns, and foundations:

$$E_{rebar} = W_R \bullet e_R \tag{16}$$

Where e_R is the total embodied carbon factors for steel reinforcement and W_R is the weight of the rebars in kg.

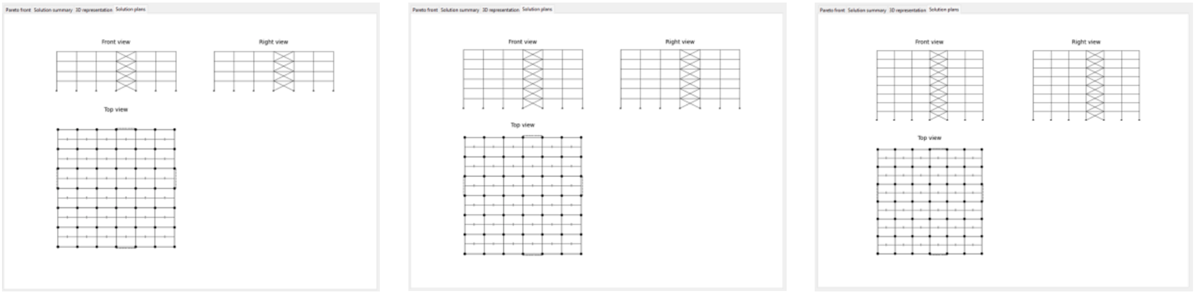
The total embodied CO_2 is:

$$Emissions = E_{structure} + E_{floor} + E_{rebar} \tag{17}$$

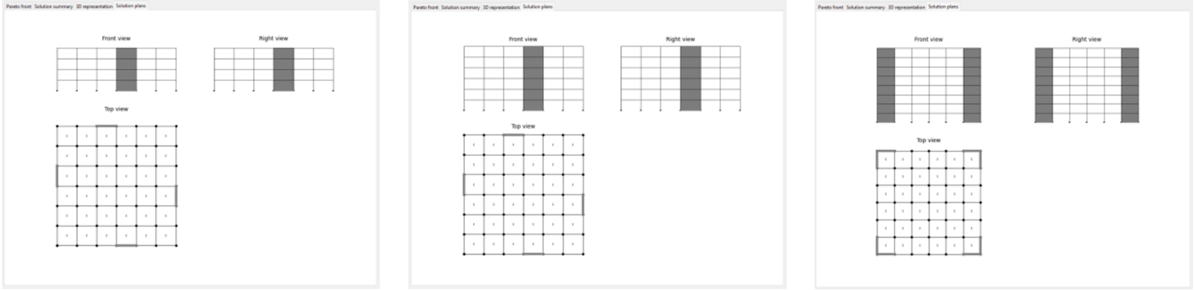
The embodied carbon values have the unit by Gross Internal Area (GIA), commonly quoted as $kgCO_2e/m^2$ GIA.

2.3. *Repair module of the calculation tool*

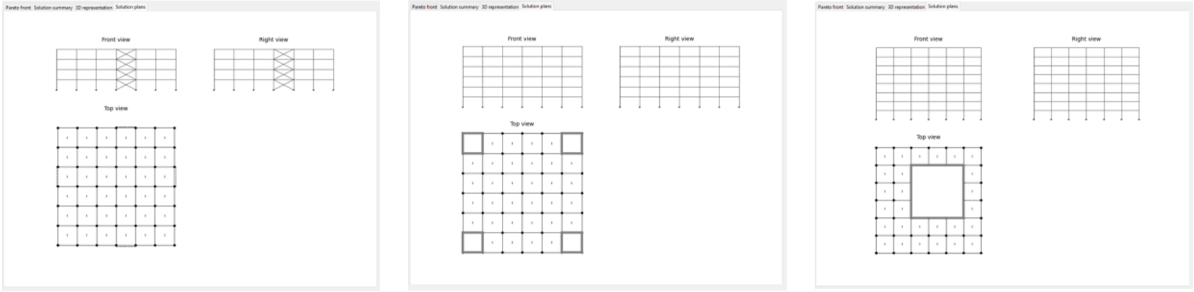
The incompatibilities between material and floor type, and between the floor type and span lengths are summarized in Table 6 and Table 7 respectively. The span length capacity of RC and steel buildings is taken from the previous research of Kanyilmaz et al. [17,18]. The references



4 storeys (steel) 6 storeys (steel) 8 storeys (steel)

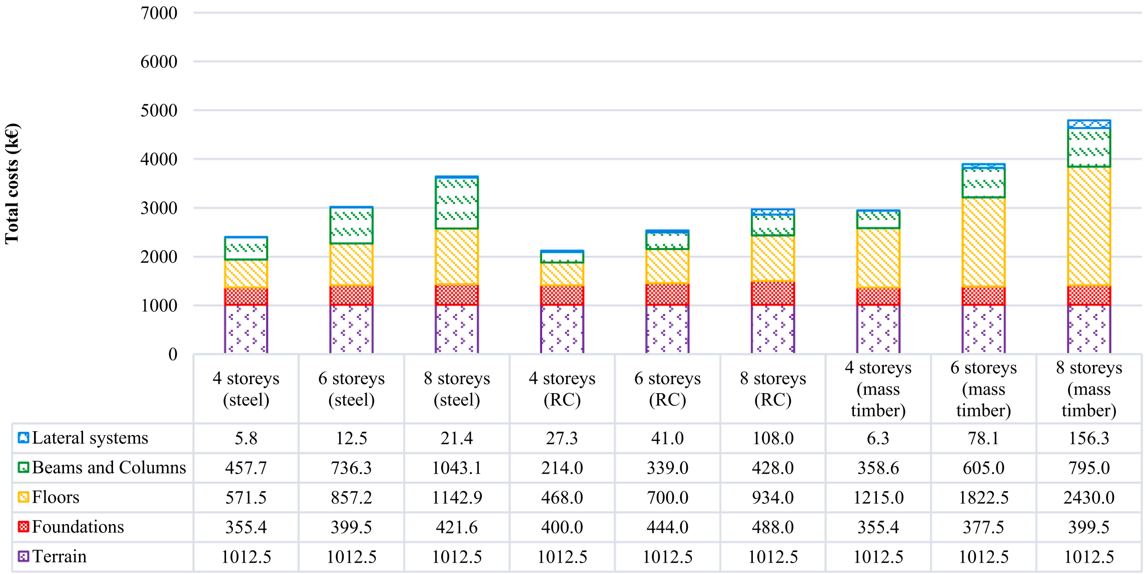


4 storeys (RC) 6 storeys (RC) 8 storeys (RC)



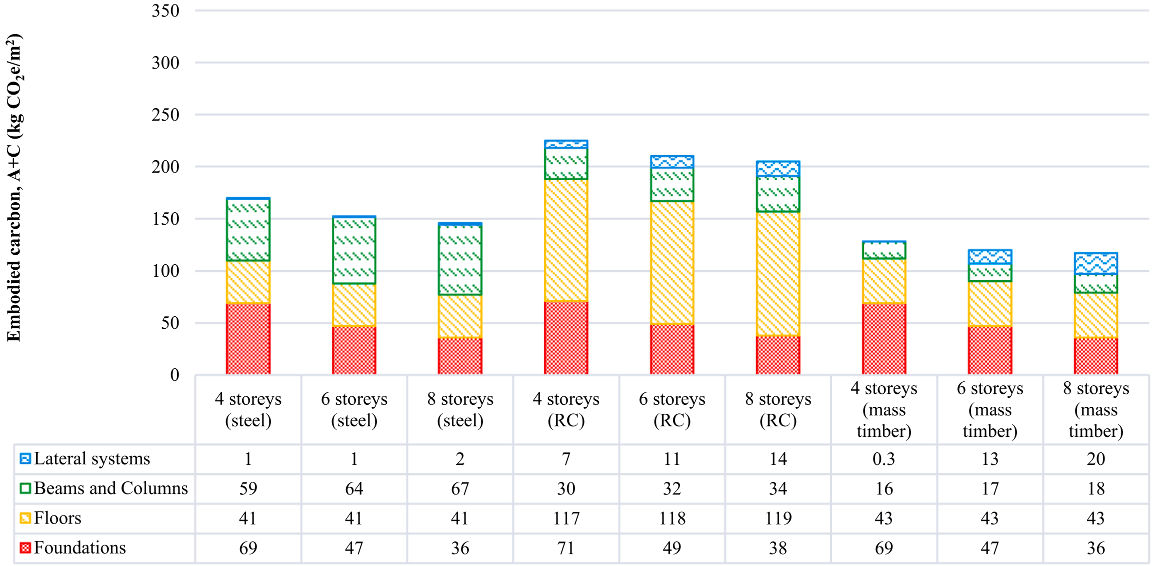
4 storeys (mass timber) 6 storeys (mass timber) 8 storeys (mass timber)

Fig. 10. Output plan views.



	4 storeys (steel)	6 storeys (steel)	8 storeys (steel)	4 storeys (RC)	6 storeys (RC)	8 storeys (RC)	4 storeys (mass timber)	6 storeys (mass timber)	8 storeys (mass timber)
Lateral systems	5.8	12.5	21.4	27.3	41.0	108.0	6.3	78.1	156.3
Beams and Columns	457.7	736.3	1043.1	214.0	339.0	428.0	358.6	605.0	795.0
Floors	571.5	857.2	1142.9	468.0	700.0	934.0	1215.0	1822.5	2430.0
Foundations	355.4	399.5	421.6	400.0	444.0	488.0	355.4	377.5	399.5
Terrain	1012.5	1012.5	1012.5	1012.5	1012.5	1012.5	1012.5	1012.5	1012.5

Fig. 11. Total cost comparison between different building storeys.



	4 storeys (steel)	6 storeys (steel)	8 storeys (steel)	4 storeys (RC)	6 storeys (RC)	8 storeys (RC)	4 storeys (mass timber)	6 storeys (mass timber)	8 storeys (mass timber)
Lateral systems	1	1	2	7	11	14	0.3	13	20
Beams and Columns	59	64	67	30	32	34	16	17	18
Floors	41	41	41	117	118	119	43	43	43
Foundations	69	47	36	71	49	38	69	47	36

Fig. 12. Embodied carbon emissions (kg CO_2e/m^2) comparison between different building storeys (Modules A + C).

for the mass timber floors are from Norman et al. [57], Structurlam and Stora Enso's design guide [58,59].

2.4. Validation of the tool on worked examples

To validate the tool calculations, we ran simulations for three buildings (steel, reinforced concrete, and mass timber) designed and simulated by other authors in the literature. We also provided additional insights on how the benchmark case studies could have been enhanced using our tool, concerning embodied carbon, cost, and free space considerations. The tool utilizes a multi-objective optimization technique to generate Pareto fronts (as explained in detail in our previous articles [17,18]). In our context, the Pareto front showcases a range of design alternatives that offer different trade-offs between embodied carbon and other building characteristics (e.g., cost, floor depth, materials used). This can empower architects and engineers to make informed decisions by selecting a design from the Pareto front that best aligns with their specific priorities, such as minimizing embodied carbon while adhering to floor depth constraints or other design preferences. In the below case studies, referring to the Table 5, we used the carbon coefficients of no.1 for steel, no.2 for concrete, no.4 for mass timber, respectively.

2.4.1. Case study 1: 6-storey office building

The input data is reported in Table 8 (Buro Happold) [60]. The input parameters considered (e.g. floor type, LLRS, beam and column sizes), and the solution summary are shown in Table 9. We compared the total embodied of the benchmark solution with the value calculated by our tool for a similar sized bay. The embodied CO_2 of life cycle modules A1-A3 of RC, steel, and timber are 331 kg/m^2 per GIA, 220 kg/m^2, and 134 kg/m^2 per GIA, respectively. These values are almost equivalent to the

Table 16
Input parameters.

Total floor area	2304 m^2	Slab type-steel frame	RC composite slab
Number of storeys	1/2/4	Slab type-RC frame	One/two way or flat slab
Span length	8 m × 8 *m*	Slab type-timber frame	CLT ribbed slab
Floor-to-ceiling height	2.5 *m*	LLRS type-steel frame	Steel bracing
Imposed load	2.5 kN/m^2	LLRS type-RC frame	RC shear wall
Superimposed dead load	1.5 kN/m^2	LLRS type-timber frame	Timber bracing
Steel grade secondary	S275		
Steel grade primary	S275		
Occupancy	Residential		
Soil bearing capacity	450kN/m^2		

analysed buildings (with less than 2 % difference).

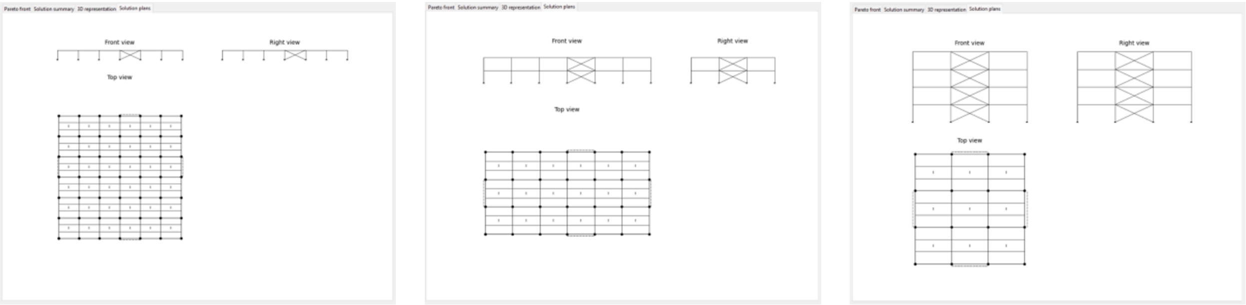
2.4.2. Case study 2: 9-storey office building

The input data (Arup and WBCSD [61]) is reported in Table 10. Table 11 lists the input parameters considered (e.g. floor type, LLRS, beam and column sizes), and the solution summary. We compared the total embodied of the benchmark solution with the value calculated by our tool for a similar sized bay. In the equivalent solution found by the tool, the embodied CO$_2$ of modules A1-A5 and A-C are 393 kg/m^2 GIA and 425 kg CO$_2$e/m^2, respectively. These results can be accepted as reliable because they only differ by 4 % from the benchmark (405 and 410 kg CO$_2$e/m^2 GIA). In the Pareto front shown in Fig. 5, other solutions are also identified with better embodied CO$_2$ performance (with less than 60 % to 80 % of embodied CO$_2$).

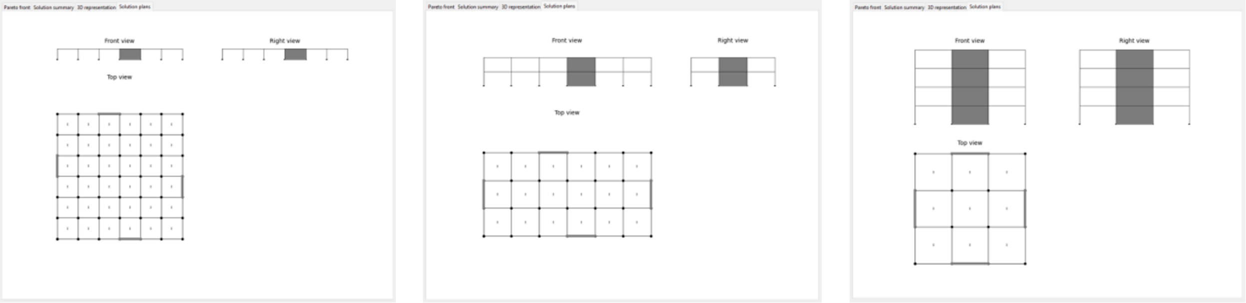
2.4.3. Case study 3: 3-storey office building

The brief design specifications of the project (provided by a construction company) are shown in Table 12 (a 3-storey office building designed using steel frames and CLT slabs). The input parameters considered (e.g. floor type, LLRS, beam and column sizes), and the solution summary are shown in Table 13. We compared the total embodied of the benchmark solution with the value calculated by our tool for a similar sized bay (Fig. 6). One of the options provided by the tool (Table 13b) is equivalent to the solution found by the authors of the benchmark design (Table 13a) in terms of span lengths, LLRS, column, beam and slab profile dimensions. The structural grid of the equivalent building is 6mx8.5 m which is similar to the actual grid of the project. The beams (IPE450) and columns (HEA220) are similar to the equivalent IPE550 and HEA200 sections, respectively. The pareto graph shows alternative solutions with different cost and embodied CO$_2$ performances (Table 13c, d, and e).

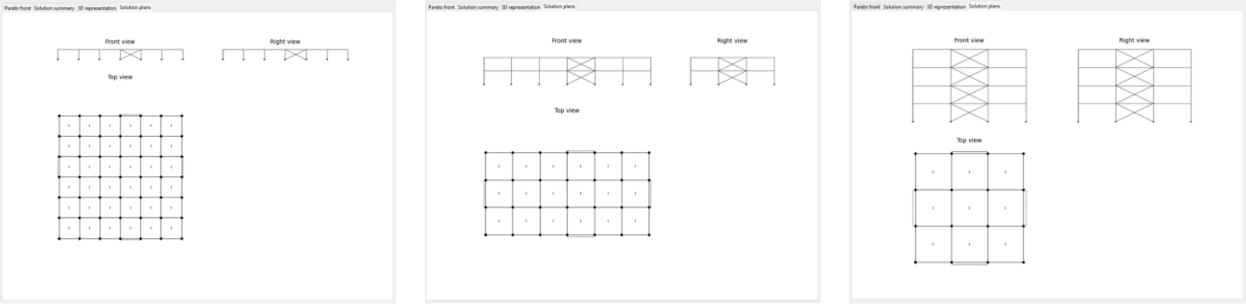
In conclusion, the tool is validated using three benchmark problems, initially designed by the engineering and construction companies. Furthermore, the tool's Pareto front outputs also suggested options with lower cost and/or embodied CO$_2$ impacts.



1 storey (steel) 2 storeys (steel) 4 storeys (steel)

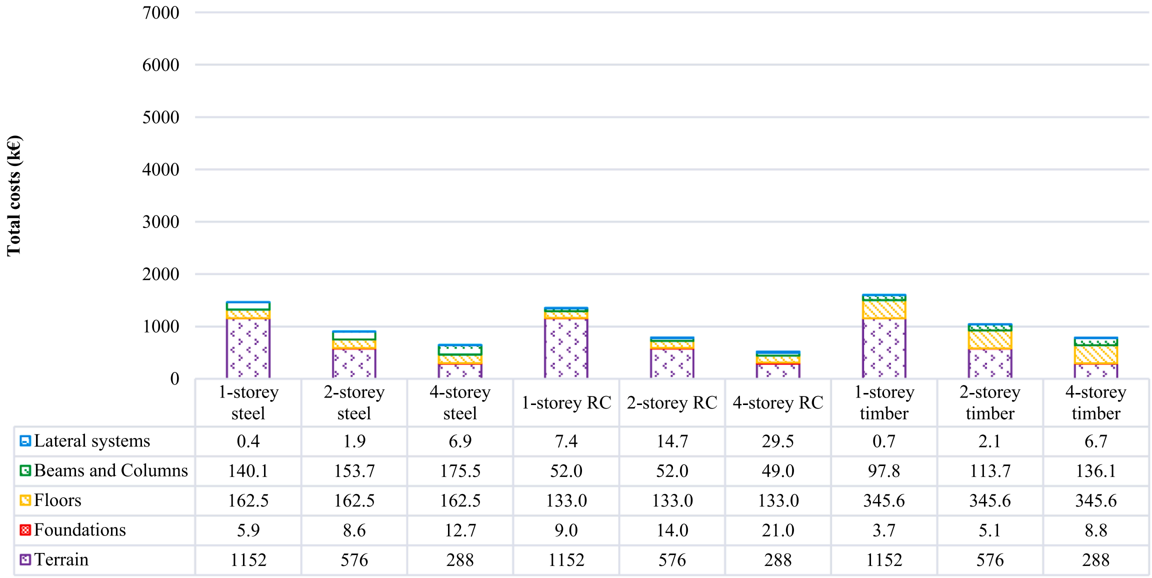


1 storey (RC) 2 storeys (RC) 4 storeys (RC)



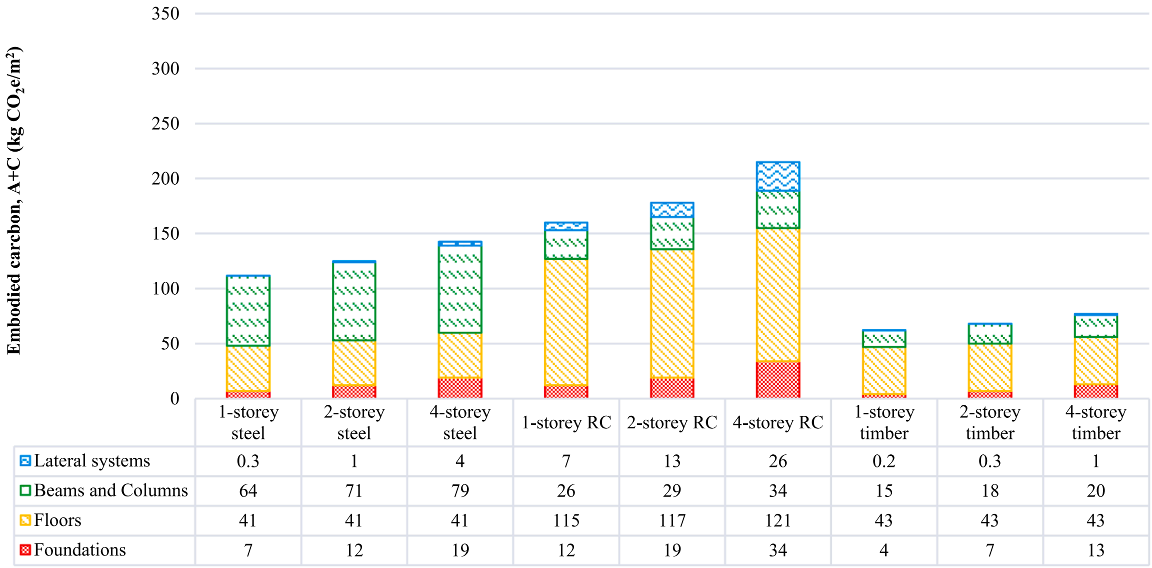
1 storey (mass timber) 2 storeys (mass timber) 4 storeys (mass timber)

Fig. 13. Output plan views (same GIA value for all structures).



	1-storey steel	2-storey steel	4-storey steel	1-storey RC	2-storey RC	4-storey RC	1-storey timber	2-storey timber	4-storey timber
▨ Lateral systems	0.4	1.9	6.9	7.4	14.7	29.5	0.7	2.1	6.7
▨ Beams and Columns	140.1	153.7	175.5	52.0	52.0	49.0	97.8	113.7	136.1
▨ Floors	162.5	162.5	162.5	133.0	133.0	133.0	345.6	345.6	345.6
▨ Foundations	5.9	8.6	12.7	9.0	14.0	21.0	3.7	5.1	8.8
▨ Terrain	1152	576	288	1152	576	288	1152	576	288

Fig. 14. Total cost comparison between different building shapes.



	1-storey steel	2-storey steel	4-storey steel	1-storey RC	2-storey RC	4-storey RC	1-storey timber	2-storey timber	4-storey timber
▨ Lateral systems	0.3	1	4	7	13	26	0.2	0.3	1
▨ Beams and Columns	64	71	79	26	29	34	15	18	20
▨ Floors	41	41	41	115	117	121	43	43	43
▨ Foundations	7	12	19	12	19	34	4	7	13

Fig. 15. Embodied carbon emissions (kg CO_2e/m^2) comparison between different building shapes (Modules A + C).

3. Sensitivity of the cost and embodied carbon values to the different building parameters

Cost and embodied carbon for the steel, timber and reinforced concrete buildings of different spans, heights, shapes, sources of materials, and floor types have been compared using the carbon factors in Table 5.

3.1. *The influence of building geometry*

The influence of different span lengths, building heights, and building shapes are compared. In all the subsections of 3.1, we used the carbon coefficients of no.1 for steel, no.2 for concrete, no.6 for steel reinforcement, and no.4 for mass timber from Table 5, respectively.

3.1.1. *Span length*

Buildings with three different span lengths are compared. The building's 2D configurations, and the input parameters are shown in Fig. 7 and Table 14, respectively.

Figs. 8 and 9 show the influence of span length on the costs and embodied carbon values:

- Shorter-span options reduced both building costs (by up to 40 %), and embodied carbon (by up to 35 %).
- The cost of mass timber solutions is more sensitive to changes in span length, experiencing increases of up to 55 %, compared to steel (variations up to 24 %) and reinforced concrete (variations up to 19 %) within their solution sets.
- The embodied carbon of RC solutions is more sensitive to changes in span length increasing up to 52 %, compared to steel (variations up to 39 %) and timber (variations up to 11 %) within their solution sets.
- The timber and RC floor costs and embodied carbon values increase when their spans are higher, while for the steel, there is no difference

Table 17
Input parameters.

X dimension	36 *m*	Slab type 1-timber frame	CLT flat slab
Y dimension	36 *m*	Slab type 2-timber frame	CLT two-way slab
Number of storeys	4	Slab type 3-timber frame	CLT ribbed slab
Span length	6 m × 6 *m*	Slab type 4-timber frame	CLT composite slab
Floor-to-ceiling height	2.5 *m*	LLRS type-timber frame	Timber bracing
Imposed load	2.5 kN/m^2		
Superimposed dead load	1.5 kN/m^2		
Steel grade secondary	S275		
Steel grade primary	S275		
Occupancy	Residential		
Soil bearing capacity	450kN/m^2		

between them since the floor thickness (composite-RC slab) of all steel solutions is fixed to 130 mm (when the span length increases, more secondary beams are needed, and the slab thickness remains unchanged; the cost and embodied carbon secondary beams are reflected in the “beams and columns” values).

3.1.2. Building height

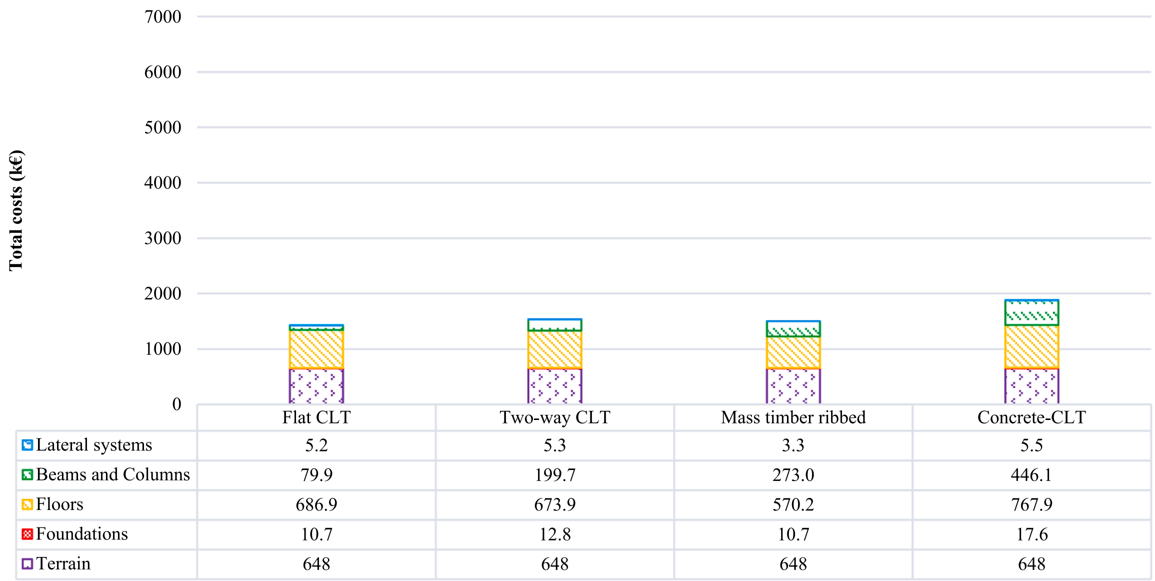
Structures with four, six, and eight-storeys are compared, all with the same building footprint (area). The input parameters, and building configurations are shown in Table 15 and Fig. 10 respectively.

Figs. 11 and 12 show the influence of building height on the costs and embodied carbon values. As the building height increases, total costs rise. However, when calculated per Gross Internal Area (in kgCO2e/m2 GIA), embodied carbon emissions decrease by 9 % for both RC and mass timber, and 14 % for steel (because the growth in floor area is proportionally greater than the growth in foundation size). However, this trend doesn’t hold for the lateral system, since the size of the lateral system and its impact on embodied carbon might not scale proportionally with

Flab sab   Two-way slab

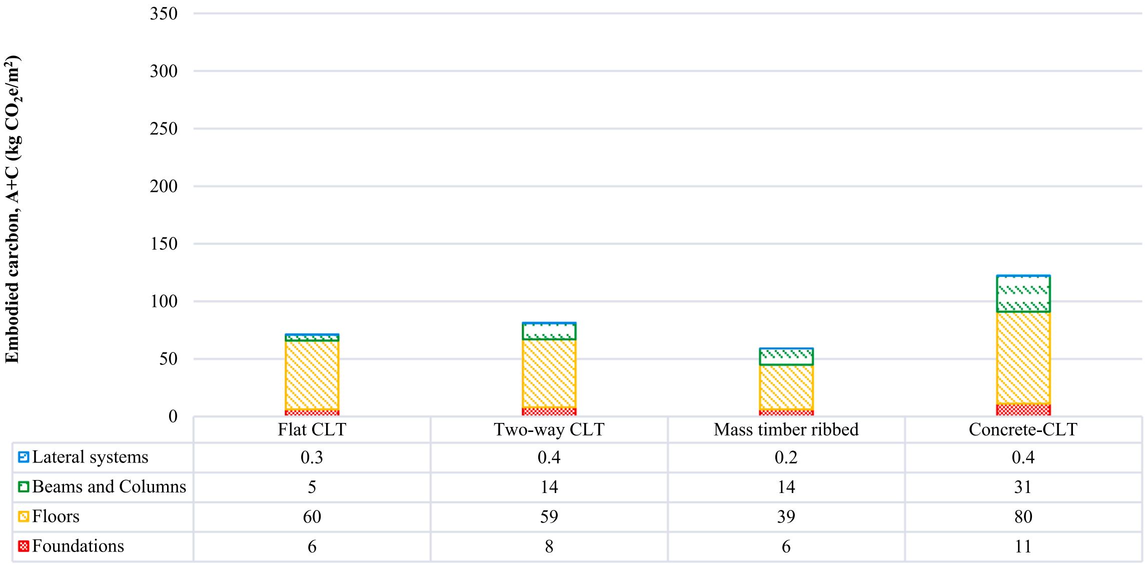
CLT-concrete slab   Ribbed slab

Fig. 16. Output plan views.



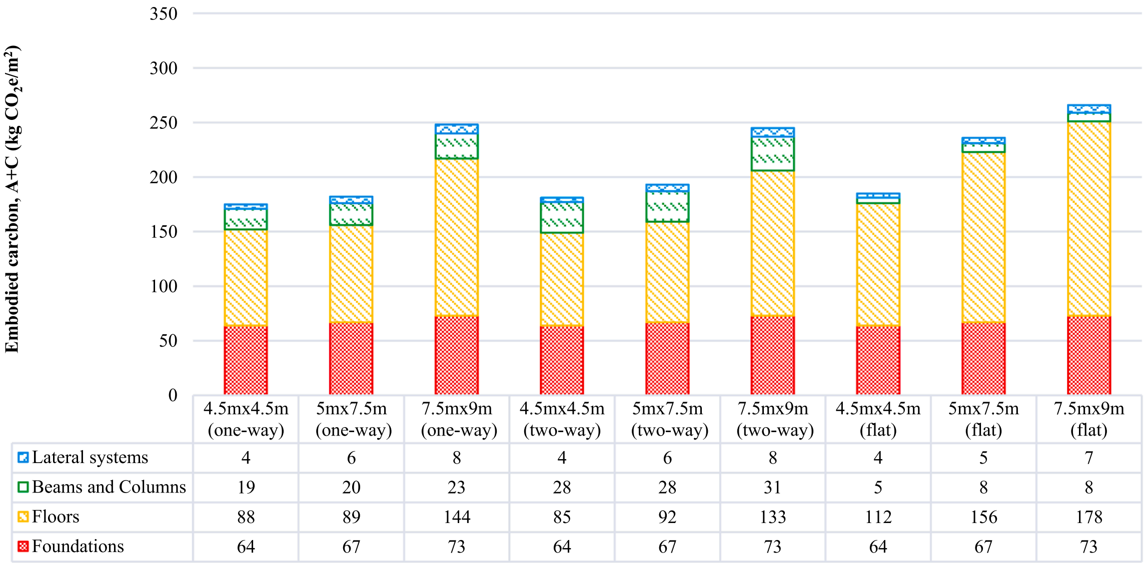
	Flat CLT	Two-way CLT	Mass timber ribbed	Concrete-CLT
Lateral systems	5.2	5.3	3.3	5.5
Beams and Columns	79.9	199.7	273.0	446.1
Floors	686.9	673.9	570.2	767.9
Foundations	10.7	12.8	10.7	17.6
Terrain	648	648	648	648

Fig. 17. Total cost comparison for different floor types.



	Flat CLT	Two-way CLT	Mass timber ribbed	Concrete-CLT
Lateral systems	0.3	0.4	0.2	0.4
Beams and Columns	5	14	14	31
Floors	60	59	39	80
Foundations	6	8	6	11

Fig. 18. Embodied carbon emissions (kg CO_2e/m^2), comparison for different floor types (Modules A + C).



	4.5mx4.5m (one-way)	5mx7.5m (one-way)	7.5mx9m (one-way)	4.5mx4.5m (two-way)	5mx7.5m (two-way)	7.5mx9m (two-way)	4.5mx4.5m (flat)	5mx7.5m (flat)	7.5mx9m (flat)
Lateral systems	4	6	8	4	6	8	4	5	7
Beams and Columns	19	20	23	28	28	31	5	8	8
Floors	88	89	144	85	92	133	112	156	178
Foundations	64	67	73	64	67	73	64	67	73

Fig. 19. Embodied carbon emissions (kg CO2e/m2), comparison for different RC floor types (Modules A + C).

the floor area. The highest impact of lateral system on the embodied carbon has been observed for the timber structures (both for increasing height, and as a general proportion). Moreover, as buildings get taller, emissions from the structural frame rise because columns must bear greater loads, leading to larger cross-sections.

3.1.3. Building shape

Different building shapes are analysed using the same total floor area achieved with different number of storeys (Table 16, Fig. 13). In other words, we kept the GIA of all structures the same, while changing the building shape: this helped us to measure the impact of building shape and height with a fixed floor area.

Figs. 14 and 15 show the influence of a building's shape on the costs and embodied carbon values:

- The cost of the land had the most significant influence in all cases, resulting in a reduction of total costs by up to 62 % as the building footprint decreased due to an increase in the number of floors. The costs of the lateral system, structural frame and foundations were higher for taller buildings.
- For all buildings, larger building footprint (building area) structures had lower embodied carbon values (ranging from 19 % to 26 %): this was due to the decreasing size of foundations, beams, columns, and lateral systems.

3.2. Floor type decisions for mass timber structures

Flat timber, two-way CLT, ribbed CLT, and CLT-concrete have been compared. The input parameters and building configurations are shown in Table 17 and Fig. 16. For the carbon factors, we used the data of no.1 for steel, no.2 for concrete, no.4 for mass timber, referring to Table 5.

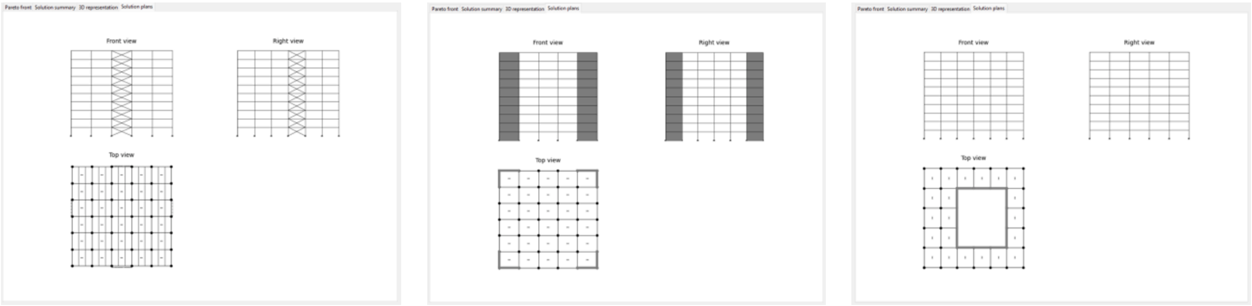
Table 18
Input parameters.

X dimension	45 *m*	Slab type-steel frame	RC composite slab
Y dimension	45 *m*	Slab type-RC frame	One/two way slab
Number of storeys	10	Slab type-timber frame	CLT ribbed slab
Span length	5 m × 7.5 *m*	LLRS type-steel frame	Steel bracing
Floor-to-ceiling height	2.5 *m*	LLRS type-RC frame	RC shear wall
Imposed load	2.5 kN/m^2	LLRS type-timber frame	Concrete core
Superimposed dead load	1.5 kN/m^2		
Steel grade secondary	S275		
Steel grade primary	S275		
Occupancy	Residential		
Soil bearing capacity	50kN/m^2		

Figs. 17 and 18 show that concrete-timber slab has the highest cost and embodied carbon due to its heavier weight resulting in heavier foundations and structural frame costs, and the ribbed CLT slab outperforms the concrete-timber slab in terms of both total cost and embodied carbon, with reductions by 17 % and 50 %, respectively. This advantage can be attributed to its lower thickness. Fig. 19 shows that the flat RC slab has a marginally higher carbon footprint compared to both one-way and two-way RC slab solutions: this can be primarily attributed to the larger slab thickness, especially at greater spans.

3.3. *Type and source of materials*

For steel structures, reused, recycled, and conventional options are compared (the carbon coefficients are taken from the EPD International AB [48], the environmental product declaration of Beltrame Group [49], and Gibbons et al. [8]). For RC structures, two different values of A1-A3 embodied carbon emissions from two concrete suppliers are used (a typical reinforced concrete (RC30, CEM I [8]) and concrete with a lower value of A1-A3 life cycle (EPD, Hanson UK [45])). For mass timber structures, the effect of forest management is analysed (sustainably managed forest and not: consequently, two different carbon coefficients are used in the life cycle stages C2-C4). The building's input parameters,

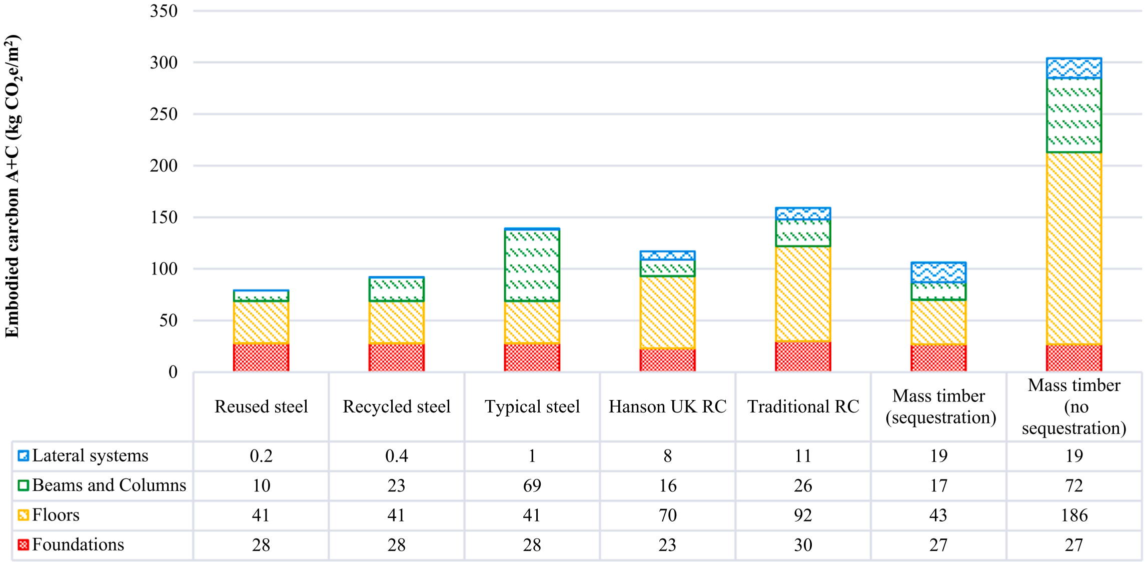


Steel

RC

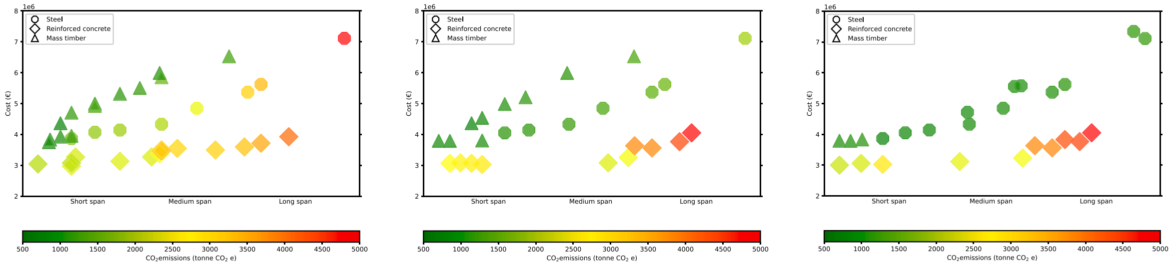
Mass timber

Fig. 20. Output plan views.



	Reused steel	Recycled steel	Typical steel	Hanson UK RC	Traditional RC	Mass timber (sequestration)	Mass timber (no sequestration)
Lateral systems	0.2	0.4	1	8	11	19	19
Beams and Columns	10	23	69	16	26	17	72
Floors	41	41	41	70	92	43	186
Foundations	28	28	28	23	30	27	27

Fig. 21. Embodied carbon emissions (kg CO$_2$e/m^2) comparison with different type and source of materials (modules A + C).



a) Typical steel b) Recycled steel c) Reused steel

Fig. 22. Comparison of solution sets with changing steel type.

Table 19
Input parameters.

X dimension	42 *m*	Slab type-steel frame	RC composite slab
Y dimension	64 *m*	Slab type-RC frame	One/two way slab
Number of storeys	8	Slab type-timber frame	CLT ribbed slab
Span length	7 m × 8 *m*	LLRS type-steel frame	Steel bracing
Floor-to-ceiling height	2.7 *m*	LLRS type-RC frame	RC shear wall
Imposed load	2.5 kN/m^2	LLRS type-timber frame	Concrete core
Superimposed dead load	1.5 kN/m^2		
Steel grade secondary	S275		
Steel grade primary	S275		
Occupancy	Residential		
Soil bearing capacity	50kN/m^2		

and the geometry output are shown in Table 18 and Fig. 20 respectively. In this analysis, referring to Table 5, we used the carbon coefficients of no.1 for typical steel, no.7 for reused steel, no.8 for recycled steel, no.2 for typical reinforced concrete, no.9 for Hanson UK concrete, no.4 for mass timber (sequestration) and no.5 for mass timber (no sequestration), respectively.

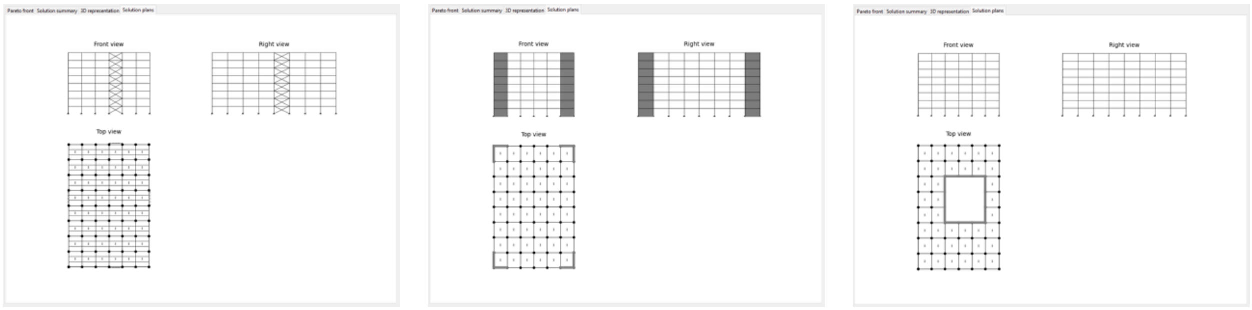
Fig. 21 shows the influence of material types on embodied carbon values:

- The structures with reused steel for beams and columns exhibited the lowest embodied carbon emissions. Their total embodied carbon values were:
- 14 % lower than structures using recycled steel.
- 43 % lower than those using typical steel.
- 25 % lower than those using mass timber, when considering carbon sequestration.
- 74 % lower than those using mass timber without accounting for carbon sequestration.
- 32 % lower than those using the most sustainable concrete option.

When focusing solely on the embodied carbon of the structural frame and excluding reinforced concrete slabs and foundations, the embodied carbon values of reused steel were lower from recycled steel by 56 % and from typical steel by 85 %.

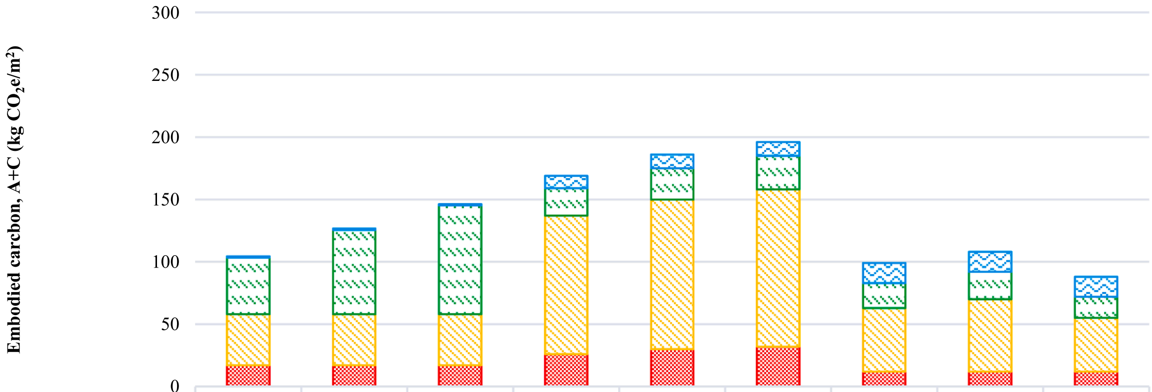
- Use of sustainable reinforced concrete (Hanson UK concrete) could reduce the total embodied carbon of RC buildings by 36 %.
- Buildings constructed using wood harvested from a non-sustainably managed forest (with no sequestration [62]), had nearly three times larger embodied carbon value compared to those made from sustainably managed timber sources.

Fig. 22 shows a significant change in the solution set composition when shifting from typical to recycled, and then to reused steel: the tool favoured steel frames over timber and RC solutions, with the former offering better cost efficiency and enhanced embodied carbon metrics. The importance of reused steel indeed has been recently also highlighted in our recent paper [63].



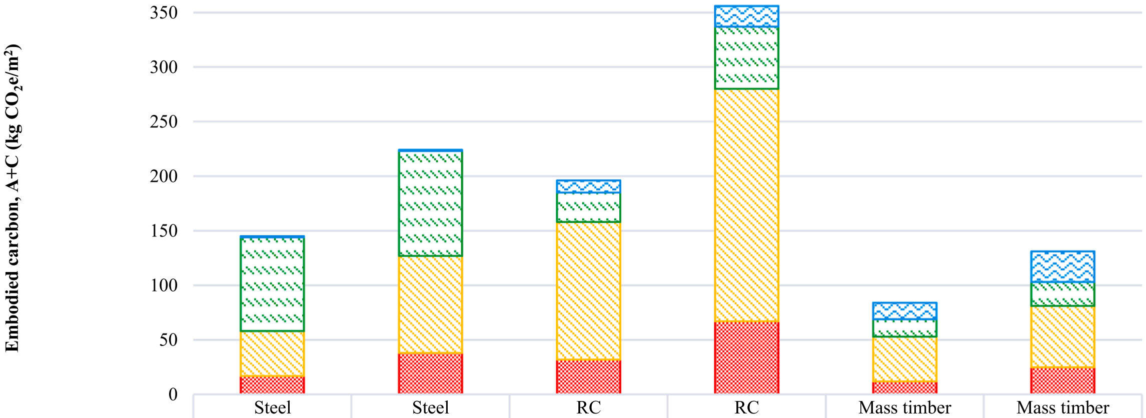
Steel RC Mass timber

Fig. 23. Output plan views.



	Steel (BE Group)	Steel (Bauforumstahl)	Steel (ICE data)	RC (Heracles)	RC (Lafarge Holcim)	RC (ICE data)	Mass timber (Zaza Timber)	Mass timber (Abobo Wood)	Mass timber (ICE data)
▨ Lateral systems	1	1	1	10	11	11	16	16	16
▨ Beams and Columns	45	68	87	22	25	27	20	22	17
▨ Floors	41	41	41	111	120	126	51	58	43
▨ Foundations	17	17	17	26	30	32	12	12	12

Fig. 24. Embodied carbon emissions (kg CO$_2$e/m^2), comparison of different databases (modules A + C).



	Steel (local)	Steel (global)	RC (local)	RC (global)	Mass timber (local)	Mass timber (global)
▨ Lateral systems	1	1	11	19	15	28
▨ Beams and Columns	86	96	27	57	16	22
▨ Floors	41	89	126	213	41	56
▨ Foundations	17	38	32	67	12	25

Fig. 25. Embodied carbon emissions comparison (kg CO$_2$e/m^2), location of supplier, modules A + C.

3.4. Sensitivity of the structure's embodied carbon results to the different EPDs and databases

The embodied carbon results are compared to show the sensitivity of different material suppliers' information with the input parameters for the same building shown in Table 19. For the embodied carbon factor values, referring to Table 5, we used the values of no.1 for typical (ICE) steel, no.10 and 11 for EPD steel, no.2 for typical (ICE) concrete, no.12 and 13 for EPD concrete, no.4 for ICE mass timber, and no.14 and 15 for EPD mass timber. The building geometries are described in Fig. 23. The difference in the material suppliers' data impacted the results by up to 40 % (Fig. 24).

The location of the supplier can also have a significant impact (up to 82 % of emissions increase) depending on whether the material is locally or globally manufactured and transported (Fig. 25). In analysis, for the same building (Table 19 and Fig. 23), the values of A4 module are taken based on two scenarios: locally manufactured (transport within a country limit of 50 km by road, A4 0.005 [8]) and globally manufactured (transport from one country to another, frequently overseas with the maximum of 10000 km by sea, A4 0.183 [8]).

4. Conclusions

This study quantified the influence of the conceptual design decisions, including material selection, building size, height and shape, span length, and floor type on the cost and carbon footprint of a building's structure. We performed a sensitivity analysis based on Non-Dominated Sorted Genetic Algorithm II method to quantitatively compare the performance of 36 different building configurations. We compared 25 material types from 15 databases (EPDs and ICE). For all the building configurations, the spectrum of embodied carbon emissions (including the steps A1, A2, A3, A4, A5, C2, C3, C4) ranged between 60 and 360 kgCO$_2$e/m2. The three major conclusions of these analyses are the following:

Building geometry (span length, height and shape) matters the most:

- Shorter-span options reduced both building costs and embodied carbon for all cases, with reductions up to 40 % in costs, 35 % in embodied carbon.
- The cost of mass timber solutions is affected more (up to 55 %) by increasing span length, with respect to steel (variations up to 24 %) and reinforced concrete (variations up to 19 %) within their solution sets.
- The embodied carbon of RC solutions is more sensitive to changes in span length, experiencing increases of up to 52 %, compared to steel (variations up to 39 %) and reinforced concrete (variations up to 11 %) within their solution sets.
- The embodied carbon emissions calculated based on Gross Internal Area (unit of kgCO$_2$e/m^2 GIA) decrease between 9 % and 14 % with increasing building height (up to 8 storeys).
- The highest impact of lateral system on the embodied carbon has been observed for the timber structures (both for increasing height, and as a general proportion).
- In general, larger building footprint (building area) structures had lower embodied carbon (ranging from 19 % to 26 %) thanks to the size decrease of foundations, beams, columns, and lateral systems.
- When building shapes are compared (for the same total area), the cost of the land had the most significant influence in all cases, resulting in a reduction of total costs by up to 62 % as the building footprint decreased due to an increase in the number of floors. This relationship can be attributed to the efficient utilization of land when constructing taller buildings.

Material type, source selection and reuse are crucial:

- Reused steel had the lowest embodied carbon emissions among all material options for the buildings analyzed: 14 % less than the recycled steel, 43 % less than typical steel, and 25 % less than mass timber (with sequestration), 74 % less than mass timber (without sequestration), and 32 % less than the most sustainable concrete.
- When we consider only the embodied carbon of the structural frame and excluding reinforced concrete slabs and foundations, the embodied carbon values of reused steel were lower from recycled steel by 56 % and from typical steel by 85 %.
- The use of a sustainable alternative to typical reinforced concrete could reduce about 36 % of the total embodied carbon of RC buildings. By sourcing timber from sustainable forests (with sequestration), the embodied carbon value in buildings can drop by 65 % compared to the non-sequestration scenario.
- The mass timber slab type influences considerably the cost and embodied carbon of the timber structure - the ribbed CLT slab outperforms the concrete-timber slab in terms of both total cost and embodied carbon, with reductions of 17 % and 50 %, respectively.
- The flat RC slab has a slightly higher carbon footprint compared to both one-way and two-way RC slab solutions because of its larger slab thickness, especially at greater spans.

Supplier Data and Location can disrupt embodied carbon calculation outcomes.

- The differences in the suppliers manufacturing emissions (obtained from their EPDs) caused variations up to 40 % among embodied carbon calculations for the same building configuration.
- The location of the supplier affected the embodied carbon results up to 82 % (whether the material is locally or globally manufactured and transported).

As a result of our sensitivity analysis, we recommend presenting a spectrum of embodied carbon results rather than a single figure in future reports and studies, particularly during conceptual design stage where various parameters can influence the outcome. By representing embodied carbon in this manner, we can highlight solutions with a median carbon footprint, and emphasize those with significant room for enhancement (for example, a timber frame incorporating sequestration might display an impressively low embodied carbon, however, without sequestration, the embodied carbon value would be considerably higher). In general, the findings indicate that architects and engineers possess considerable influence in mitigating the environmental footprint of structural systems through the careful selection of materials and system designs. When they strike a balance between cost considerations, environmental impact, and structural necessities, they can effectively create sustainable and economical buildings.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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