Supplementary Materials

From design to decarbonisation: a BIM-based comparative analysis of embodied carbon in buildings

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1. Calculation Embodied Carbon of the Traditional Houses

a. Traditional Steel House

The embodied carbon of the house according to the study would be around 104,165.16 $kgCO_2eq$, provided it was built using traditional steel building techniques. The materials utilised (measured in kilogrammes), the embodied carbon (EC) values per kilogramme of all components derived from the ICE database [1] as shown in Table S1.

Table S1. Embodied Carbon of Traditional Steel House [1]

Material Type	Material Quantity (Kg)	Unit Embodied Carbon ($kgCO_2eq/kg$)	Material Embodied Carbon ($kgCO_2eq$)
Steel, Structural	23,561.9	2.190	51,600.56
Steel, Sheet	1,697.7	2.453	4,164.45
Steel, Rebar	2,281.25	1.72	3,923.75
Concrete	92,160	0.134	12,349.44
Insulation, Mineral Wool	3,543.75	1.25	4,429.69
Cladding, Cement Fibreboard	3,724.98	0.538	2,004.04
Glass Fibre Plasterboard	3,950	0.322	1,271.90
Plasterboard	6,664.01	0.238	1,586.03
Mortar	6,084	0.146	888.26
Screed	96,921.62	0.124	12,018.28
Ceramic, Tile	2,018.84	0.796	1,606.99
Laminate	780.3	0.698	544.65
Rubber, Synthetic	13.464	2.547	34.29
Plaster	1,200	0.164	196.8
Paint	86.66	2.152	186.49
Timber Door	582.05	0.504	293.35

Aluminium, Profile	261.3	5.58	1,458.05
Double Glazed Glass	1,386.72	1.63	2,260.35
Bitumen Membrane	808.48	0.865	699.33
Lean Concrete	15,870	0.094	1,491.78
Clay, Tile	4,536	0.255	1,156.68

Carbon footprint of traditional steel house: 104,165.16 $kgCO_2eq$

b. Traditional Reinforced Concrete House

The embodied carbon of the traditional reinforced concrete house according to the study would be approximately 84,640.06. The materials utilised (measured in kilogrammes), the embodied carbon (EC) values per kilogramme of all components derived from the ICE database [1] as shown in Table S2.

Table S2. Embodied Carbon of Traditional Reinforced Concrete House[1]

Material Type	Material Quantity (Kg)	Unit Embodied Carbon ($kgCO_2eq/kg$)	Material Embodied Carbon ($kgCO_2eq$)
Steel, Rebar	7,299.55	1.72	12,555.22
Concrete	168,528	0.134	22,582.75
Clay, Brick	86,256.8	0.24	20,701.63
Insulation, Mineral Wool	2,143.23	1.25	2,679.03
Mortar	16,586	0.146	2,421.56
Screed	96,921.62	0.124	12,018.28
Ceramic, Tile	2,018.84	0.796	1,606.99
Laminate	780.3	0.698	544.65
Rubber, Synthetic	13.464	2.547	34.29
Plaster	11,888	0.164	1,949.63
Paint	86.66	2.152	186.49
Timber Door	582.05	0.504	293.35
Aluminium, Profile	261.3	5.58	1,458.05
Double Glazed Glass	1,386.72	1.63	2,260.35
Bitumen Membrane	808.48	0.865	699.33
Lean Concrete	15,870	0.094	1,491.78
Clay, Tile	4,536	0.255	1,156.68

Carbon Footprint of the Traditional Reinforced Concrete House ≈ 84,640.06 $kgCO_2eq$

c. Traditional Timber House

The embodied carbon of the traditional timber house according to the study would be approximately 51,255.87 $kgCO_2eq$. The materials utilised (measured in kilogrammes), the embodied carbon (EC) values per kilogramme of all components derived from the ICE database [1] as shown in Table S3.

Table S3. Embodied Carbon of Traditional Timber House[1]

Material Type	Material Quantity (Kg)	Unit Embodied Carbon ($kgCO_2eq/kg$)	Material Embodied Carbon ($kgCO_2eq$)
Timber Structure, I Beam	9,441.19	0.483	4,560.09
Timber Floor, Plywood	4,480	0.681	3,050.88
Steel, Rebar	2,281.25	1.72	3,923.75
Concrete	92,160	0.134	12,349.4
Insulation, Mineral Wool	3,543.75	1.25	4,429.69

Internal Cladding, Hardwood	4,584.06	0.815	3,736.01
External Cladding, Wood-plastic	3,619	1.44	5,211.36
MDF	4,160	0.856	3,560.96
Mortar	6,084	0.146	888.26
Ceramic, Tile	2,018.84	0.796	1,606.99
Laminate	780.3	0.698	544.65
Rubber, Synthetic	13.464	2.547	34.29
Timber Door	582.05	0.504	293.35
Aluminium, Profile	261.3	5.58	1,458.05
Double Glazed Glass	1,386.72	1.63	2,260.35
Bitumen Membrane	808.48	0.865	699.33
Lean Concrete	15,870	0.094	1,491.78
Clay, Tile	4,536	0.255	1,156.68

Carbon footprint of the timber house ≈ 51,255.87 kgCO$_2$eq

2. Calculation Low Embodied Carbon of the Houses

a. Low Embodied Carbon Steel House

The house according to the study would be approximately 62,018.3 kgCO$_2$eq, provided it was built using low embodied steel building materials and the overall carbon footprint associated with these materials are all shown in Table S4. The materials utilised (measured in kilogrammes), the embodied carbon (EC) values per kilogramme of all components derived from the ICE database [1] as shown in Table S4.

Table S4. Low Embodied Carbon of Steel House

Material Type	Material Quantity (Kg)	Unit Embodied Carbon (kgCO$_2$eq/kg)	Material Embodied Carbon (kgCO$_2$eq)	Reference
Low carbon Steel, Structural	23,561.9	0.975	22,972.85	[1]
Low Carbon Steel, Sheet	1,697.7	0.643	1,091.62	[1]
Low Carbon Steel, Rebar	2,281.25	0.73	1,665.31	[1]
Low Carbon Concrete	92,160	0.101	9,308.16	[1]
Insulation, Polyisocyanurate (PIR)	775.05	3.089	2,394.13	[1]
Cladding, Cement Fibreboard	3,724.98	0.538	2,004.04	[1]
Glass Fibre Plasterboard	3,950	0.322	1,271.90	[1]
Plasterboard	6,664.01	0.238	1,586.03	[1]
Low Carbon Mortar	6,084	0.088	535.39	[1]
Low Carbon Screed	96,921.62	0.111	10,758.30	[1]
Ceramic, Tile	2,018.84	0.796	1,606.99	[1]
Laminate	780.3	0.698	544.65	[1]
Rubber, Synthetic	13.464	2.547	34.29	[1]
Plaster	1,200	0.164	196.8	[1]
Paint	86.66	2.152	186.49	[1]
Timber Door	582.05	0.504	293.35	[1]
Low Carbon Aluminium, Profile	261.3	1.304	340.74	[1]
Double Glazed Glass	1,386.72	1.63	2,260.35	[1]
Bitumen Membrane	808.48	0.865	699.33	[1]
Low Carbon Lean Concrete	15,870	0.070	1,110.9	[1]
Clay, Tile	4,536	0.255	1,156.68	[1]

Carbon footprint of the low embodied carbon steel house ≈ 62,018.3 kgCO$_2$eq

b. Low Embodied Carbon of Reinforced Concrete House

The house according to the study would be around 57,412.58 kgCO$_2$eq, provided it was built using low embodied reinforced concrete building materials. The materials utilised (measured in kilogrammes), the embodied carbon (EC) values per kilogramme of all components derived from the ICE database [1] or other academic paper [2] as shown in Table S5.

Table S5. Low Embodied Carbon of Reinforced Concrete House

Material Type	Material Quantity (Kg)	Unit Embodied Carbon (kgCO$_2$eq/kg)	Material Embodied Carbon (kgCO$_2$eq)	Reference
Low Carbon Steel, Rebar	7,299.5	0.73	5,328.63	[1]
Low Carbon Concrete	168,528	0.101	17,021.33	[1]
Sandstone, Brick	86,256.8	0.13	11,213.38	[2]
Insulation, Polyisocyanurate (PIR)	468.75	3.089	1,447.97	[1]
Low Carbon Mortar	16,586	0.088	1,459.57	[1]
Low Carbon Screed	96,921.62	0.111	10,758.30	[1]
Ceramic, Tile	2,018.84	0.796	1,606.99	[1]
Laminate	780.3	0.698	544.65	[1]
Rubber, Synthetic	13.464	2.547	34.29	[1]
Plaster	11,888	0.164	1,949.63	[1]
Paint	86.66	2.152	186.49	[1]
Timber Door	582.05	0.504	293.35	[1]
Low Carbon Aluminium, Profile	261.3	1.304	340.74	[1]
Double Glazed Glass	1,386.72	1.63	2,260.35	[1]
Bitumen Membrane	808.48	0.865	699.33	[1]
Low Carbon Lean Concrete	15,870	0.070	1,110.9	[1]
Clay, Tile	4,536	0.255	1,156.68	[1]
Carbon footprint of low embodied carbon reinforced concrete house ≈ 57,412.58 kgCO$_2$eq				

c. Low Embodied Carbon of Timber House

The house according to the study would be approximately 41,191.54 kgCO2eq, provided it was built using low embodied timber building materials. The materials utilised (measured in kilogrammes), the embodied carbon (EC) values per kilogramme of all components derived from the ICE database [1], and the overall carbon footprint associated with these materials are all shown in Table S6.

Table S6. Low Embodied Carbon of Timber House

Material Type	Material Quantity (Kg)	Unit Embodied Carbon (kgCO$_2$eq/kg)	Material Embodied Carbon (kgCO$_2$eq)	Reference
Timber Structure, LVL	9,441.19	0.390	3,682.06	[1]
Timber Floor, Plywood	4,480	0.681	3,050.88	[1]
Low Carbon Steel, Rebar	2,281.25	0.73	1,665.31	[1]
Low Carbon Concrete	92,160	0.101	9,308.16	[1]
Insulation, Polyisocyanurate (PIR)	775.05	3.089	2,394.13	[1]
Internal Cladding, Hardwood	4,584.06	0.815	3,736.01	[1]
External Cladding, Wood-plastic	3,619	1.44	5,211.36	[1]
MDF	4,160	0.856	3,560.96	[1]
Low Carbon Mortar	6,084	0.088	535.39	[1]
Ceramic, Tile	2,018.84	0.796	1,606.99	[1]
Laminate	780.3	0.698	544.65	[1]
Rubber, Synthetic	13.464	2.547	34.29	[1]

Timber Door	582.05	0.504	293.35	[1]
Low Carbon Aluminium, Profile	261.3	1.304	340.74	[1]
Double Glazed Glass	1,386.72	1.63	2,260.35	[1]
Bitumen Membrane	808.48	0.865	699.33	[1]
Low Carbon Lean Concrete	15,870	0.070	1,110.9	[1]
Clay, Tile	4,536	0.255	1,156.68	[1]

Carbon footprint of low embodied carbon timber house ≈ 41,191.54 kgCO$_2$eq

3. Reduction of Embodied Carbon in Building Materials

It is critical to reduce the embodied carbon of building materials in order to promote a transition to a low-carbon built environment, mitigate climate change, and encourage sustainable resource management [3]. Decreasing buildings' embodied carbon dioxide equivalent (embodied CO$_2$eq) is a crucial response to national and international carbon reduction targets [4]. Reducing the embodied carbon in building materials has been attempted on various strategies. These efforts include the developing of novel bio-based natural materials, the application of advanced construction methods, the use of locally sourced, durable, low-maintenance materials, and the integration of renewable energy into the shipping and production industries [5]. Reducing the embodied carbon of concrete is therefore essential. A number of low-carbon technologies and techniques have been developed to address potentially eliminate the carbon emissions that are related to the construction of concrete [6, 7, 8]

Increasing utilisation of supplementary cementitious materials (SCMs) such as fly ash and slag to partially replace Portland cement clinker, as well as developing a substitute binders and alkali-activated materials with lower CO2 emissions, are the ways to lower carbon emissions in cement-based materials. Additionally, by improved concrete mix designs, improved structural designs, material recycling, and more effective production and building methods throughout the life cycle of cement-based products, emissions can be reduced by increasing the efficiency of cement usage [9]. As a result, the emission values considered in this study reflect levels that are likely attained in the current market using commonly employed procedures that have been found in life-cycle assessment studies. These methods can lower the embodied carbon in concrete to 0.101 kgCO$_2$eq/kg and in lean concrete to 0.070 kgCO$_2$eq/kg, and in mortar and screed may be decreased to 0.088 and 0.111 kgCO$_2$eq/kg, respectively [1]. Minimising steel's embodied carbon is essential to achieving sustainable building practices. Steel sector decarbonisation necessitates a transition from coal-based metallurgy to one based on hydrogen and electricity [10]. GHG emissions can be decreased by interim measures such using pre-reduced iron ores in a blast furnace and injecting hydrogen. The study's decreased emission factors are based on steel manufacturing pathways that utilise a large percentage of recycled scrap that is processed in electric arc furnaces, which consume significantly less energy than traditional blast furnace-basic oxygen furnace paths. As a result, the values obtained in this study represent achievable emission reductions by employing commonly employed practices. By using these techniques, the embodied carbon in steel products can be reduced to 0.975 kgCO$_2$eq/kg for steel structural, 0.643 kgCO$_2$eq/kg for steel sheet, and 0.73 kgCO$_2$eq/kg for rebar [1].

The usage of LVL, an engineered wood product comprised of thin glued wood veneers, in structural applications has grown because of its improved mechanical performance and sustainability [11]. The carbon footprint of timber structure material can be lowered to 0.390 kgCO$_2$eq/kg by using LVL [1]. As a result, the values worked in this research indicate viable low-carbon material possibilities that take into account regional material availability and current manufacturing techniques in sustainable construction. Buildings constructed with low-carbon bricks have the potential to significantly reduce their total carbon footprint. So, the building's total embodied carbon could be substantially decreased with sandstone brick, which has an embodied carbon of 0.13 $kgCO_2eq/kg$ [12]. Mineral wool was utilised in this study, its embodied carbon is 1.25 $kgCO_2eq/kg$ [1], to insulate the traditional building envelope, Polyisocyanurate (PIR), its embodied carbon is 3.089 $kgCO_2qe/kg$ [1], was used for low embodied carbon house. Mineral wool has less embodied carbon than PIR if a per kg comparison is performed, but this does not account for the mass of insulation material required to achieve a particular R-value, which is important for a material for insulation where significant greenhouse gas emissions can be minimised in usage [13]. According to UK Building Regulations, each material's insulation thickness was calculated to achieve the same target thermal performance for exterior walls (U = 0.18 W/m^2K) in order to ensure functional equivalency [14]. Based on this study, equal thermal resistance can be obtained with around 17.55 kg/m^2 of mineral wool or 3.84 kg/m^2 of PIR insulation utilising standard heat transfer ratios. Therefore, mineral wool is around 4.57 times heavier per square metre than PIR for similar heat resistance. It should be mentioned that these figures could change based on the configuration of the walls and the specific thermal properties of the materials selected. The use of PIR insulation can significantly lower the material's overall carbon footprint when the R-value is taken into account because less material is required overall. Therefore, the total embodied carbon associated with the insulation layer can be decreased even while the embodied carbon per kilogram is higher due to the smaller mass of PIR required to obtain the same insulating performance.

4. Sensitivity Analysis

A one-at-a-time (OAT) parametric sensitivity analysis was performed in to assess the robustness of the embodied carbon results in relation to variability in emission factor data. While all other parameters (material quantities, building form, and non-dominant EFs) remained fixed, the emission factors (EFs) of the dominating materials were individually changed by 10% and 20% from their ICE database baseline values. These materials were selected as, when taken as a whole, they constitute the majority of all embodied carbon in all three structural systems. Table 1 analyses the robustness of the embodied carbon results.

Uncertainty in the ICE emission factor values themselves, which results from the averaging of heterogeneous production data within the database, and variability in real-world material carbon intensity, which reflects variations in manufacturing processes, energy sources, and supply chain geographies across the UK market, are two separate but related sources of input variation that are addressed by the sensitivity analysis. By changing emission factors by 10% and 20%, the research obtains a range that matches with the observed inter-database spread for key building materials. Emission factors have been defined to be average values with inherent uncertainty and variability. While variability includes temporal variability, spatial variability, and variability between objects and sources, uncertainty is divided into parameter uncertainty, model uncertainty, and uncertainty resulting from rational choices [15]. Therefore, it is important to interpret the results not only as a parametric test but also as a measure of how conclusions might shift in real-world scenarios involving material and supply chain variability.

Structural steel accounts for around 49.5% of the total embodied carbon (51,600 kgCO2eq) in a traditional steel house, leading it to be most predominant material. Concrete, the second largest contributor at 11.9%, shows a significantly lower sensitivity of ±2.4% under the same variation. A ±20% variation in its emission factor results in a total building embodied carbon range of approximately 93,845 to 114,485 $kgCO_2eq$, representing a change of around ±9.9% from the baseline of 104,165 $kgCO_2eq$. Of the three materials evaluated, cladding materials (which include fibre board, glass fibre plasterboard, and plasterboard) contribute around 4.7% of total emissions. As a result, they show not much sensitivity, with a ±20% difference resulting in a total change of only ±0.9%. This demonstrates that secondary materials have a minor impact on the overall total and that the steel house findings are mostly sensitive to structural steel emission factor uncertainty.

Table S7. Estimated Sensitivity of Total Embodied Carbon to EF (±10% and ±20%)

Structure	Material Varied	EF Change	Total EC ($kgCO_2eq$)	Δ from Baseline
Traditional Steel House	Structural Steel	−20%	93,845	−9.9%
		−10%	99,005	−4.9%
		Baseline	104,165	—
		+10%	109,325	+4.9%
		+20%	114,485	+9.9%
	Concrete	−20%	101,697	−2.4%
		−10%	102,931	−1.2%
		Baseline	104,165	—
		+10%	105,399	+1.2%
		+20%	106,633	+2.4%
	Cladding (fibre board, glass fibre plasterboard, plasterboard)	−20%	103,193	−0.9%
		−10%	103,679	−0.5%
		Baseline	104,165	—
		+10%	104,651	+0.5%
		+20%	105,137	+0.9%
Traditional Reinforced Concrete House	Concrete	−20%	80,123	−5.3%
		−10%	82,382	−2.7%
		Baseline	84,640	—
		+10%	86,898	+2.7%
		+20%	89,157	+5.3%
	Steel Rebar	−20%	82,129	−2.9%
		−10%	83,385	−1.5%
		Baseline	84,640	—
		+10%	85,895	+1.5%
		+20%	87,151	+2.9%
	Brick (cladding)	−20%	80,496	−4.9%
		−10%	82,568	−2.4%
		Baseline	84,640	—
		+10%	86,712	+2.4%

		+20%	88,784	+4.9%
Tradational Timber House	Structural Timber	−20%	50,344	−1.8%
		−10%	50,800	−0.9%
		Baseline	51,256	—
		+10%	51,712	+0.9%
		+20%	52,168	+1.8%
	Concrete	−20%	48,787	−4.8%
		−10%	50,022	−2.4%
		Baseline	51,256	—
		+10%	52,491	+2.4%
		+20%	53,725	+4.8%
	Cladding (hardboard, wood-plastic board, MDF)	−20%	48,754	−4.9%
		−10%	50,005	−2.4%
		Baseline	51,256	—
		+10%	52,507	+2.4%
		+20%	53,758	+4.9%

EF = Emission Factor derived from the ICE Database.

Emissions are more distributed equally across three main material groups for the traditional reinforced concrete house. Under ±20% EF change, concrete, the most significant component at 26.7%, results in a total embodied carbon shift of about ±5.3%. With a contribution of 24.5%, brick cladding has a nearly equal sensitivity of ±4.9%. A lower shift of around ±2.9% is produced by steel rebar, which accounts for 14.8% of total emissions. Uncertainty in any one emission component has a proportionately effect on the final result due to the comparatively balanced distribution of emissions among these three materials. The sensitivity analysis highlights a significant difference between the structural timber and the other dominant materials for the traditional timber house. Despite being the system's defining material, structural timber contributes only about 8.9% of total embodied carbon (4,560 $kgCO_2eq$). As a result, it has the lowest sensitivity of all the materials assessed in all three systems, with a ±20% variation resulting in a total change of only ±1.8%. In contrast, with ±20% fluctuation, concrete and cladding materials (hardboard, wood-plastic board, and MDF) each contribute around 24% of total emissions and demonstrate greater sensitivity of ±4.8% and ±4.9%, respectively. This result emphasises the way other elements, especially concrete foundations and cladding components, contribute a disproportionate amount of embodied carbon uncertainty in timber-based construction.

The sensitivity demonstrates that a 20% shift in the emission factor of a single dominating material results in a change in total building embodied carbon of no more than about 10% across all three structural systems. Crucially, all sensitivity scenarios maintain the relative ranking of the three structural systems, with steel producing the most embodied carbon and timber producing the lowest, followed by reinforced concrete. This demonstrates that the study's comparison conclusions are robust to realistic variability in emission factor data.

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