“Mapping material use and modelling the embodied carbon in UK construction” Supporting information for papers

“Mapping material use and embodied carbon in the UK construction”
and
“Modelling the embodied carbon cost of UK domestic building construction: Today to 2050”

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1 The UK’s material footprint

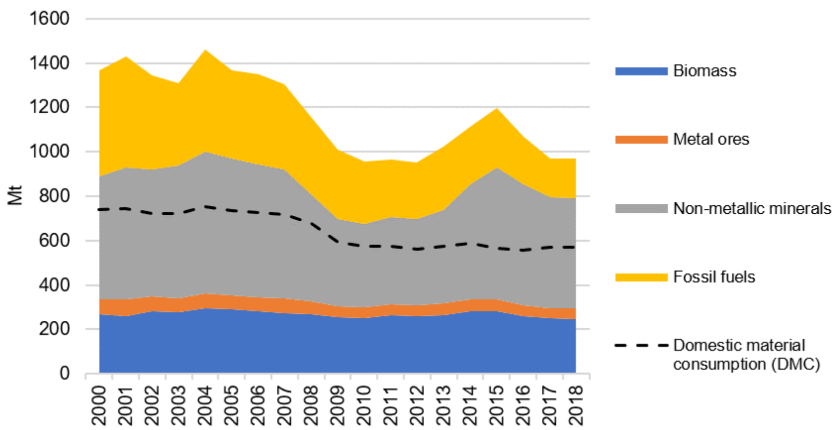


Figure 1: The UK’s material footprint by the four constituent material groups and UK’s domestic material consumption (DMC) [1].
Data sources: Biomass - Defra, Food and Agriculture Organisation of the United Nations, Eurostat, Kentish Cobnuts Association; Metal ores, Non-metallic minerals - British Geological Survey; Fossil energy materials or carriers - BEIS

The UK’s material footprint was 971 Mt in 2018, equivalent to 14.6 t/capita, whereas domestic material consumption (DMC) calculated as domestic extraction plus imports and minus exports 569 Mt (Fig. 1). The largest category, non-metallic materials such as cement, ceramics, glass, limestone, clay, marble, sand and gravel, are primarily used in construction. High level data on specific materials used in construction reported by the UK Trade Associations or UK official Statistics are included in the Table 33.

The British Construction Steel Association (BCSA) [2] reported the consumption of constructional steelworks (rolled sections, fabricated sections, hollow sections and light sections) in construction as 0.9 Mt in 2018. The largest share, as much as 77%, was attributed to non-residential buildings, followed by infrastructural projects (17%). Agriculture, domestic buildings and other sectors did not exceed 2% or consumption of constructional steelworks. Among non-residential buildings, the largest sectors were industrial buildings (64%) and office buildings (15%).

The European Ready Mixed Concrete Organisation (ERMCO) [3] reported that concrete production in the UK was 90 Mt in 2018, 61% of was ready-mix concrete (RMC). More than a half of RMC (55%) was used in buildings (29.7 Mt), 25% in infrastructure, 5% concrete roads, 5% pavements and 10% in other uses.

These statistics do not show the share of ready-mix concrete used for domestic and non-domestic buildings. ERMCO reported that 41% of concrete was used as precast (PC) or off-site manufactured concrete. The average cement content in RMC was 278 kg/m^3, the average cement content in PC is not known. The total consumption of concrete blocks in the UK was approximately 9 Mt [4].

Total UK cement consumption in 2018 was reported as 11.7 Mt (Mineral Products Association, MPA) [5], 78% of which was produced in the UK [6]. More than a half of cement was used for RMC, a quarter in products, 17% in 'Merchant' and the rest was classified as 'Other'. The MPA does not provide detailed information on end use of cement. Shanks et al. [7] estimated that the domestic building sector consumed approximately 4.6 Mt out of 13 Mt of cementitious materials[1] in 2014. Since then, cementitious materials consumption has increased, reaching 15.6 Mt in 2021 [8].

In 2018, imports of steel reinforcement for concrete were approximately 0.5 Mt [9], with overall consumption approximately 0.9 Mt [10]. No information is available on the end use of steel reinforcement.

According to the "Monthly Statistics of Building Materials and Components" [4] total consumption of bricks in 2018 was approximately 5.5 Mt.

The UK's consumption of timber and panel products in 2018 was reported as 17.2 million m^3 [11], of which 10 million m^3 was sawn and planed softwood. 3.7 million m^3 was produced in the UK, and 6.3 million m^3 was imported. Approximately 27% of UK-produced sawn softwood, and over 60% of that imported, was destined for construction, totalling 4.8 million m^3. The Timber Trade Federation (TTF) does not report the timber used for new housing, nevertheless the latest issues of the Timber Utilisation Statistics published in 2015 [12] reported that 555 thousand m^3 of sawn softwood was used to deliver 177 thousand new houses [8] and 5,395 thousand m^3 was used in "Other construction". In 2018, 250 thousand new dwellings were completed in the UK. The sawn softwood intensity per new housing increased from 2.79 to 3.13 kg/m^2 in years 2010 to 2014 [12, 8], so keeping this trend we can expect 2018 sawn softwood consumption to be at the level of 970k m^3, equivalent of 500 kt (density 515 kg/m^3). No detailed information is given on what "Other construction" includes and how this consumption has changed since 2015.

2 Emissions in the UK

The UK's total 2018 GHG emissions were 703 $MtCO_{2e}$ [13], of which 537 $MtCO_{2e}$ are territorial (including international aviation and shipping) [14]. Manufacturing of materials in the UK represented 60 $MtCO_{2e}$, 86% of which were from fuel combustion and 14% were process emissions (which arose from a range of chemical reactions including the calcination of limestone in cement production [15]). Direct and indirect GHG emissions from buildings (operational emissions) accounted for 23% UK territorial GHG emissions [16], with 12% from manufacturing and construction [17]. Apart from "Cement and Lime" which is mainly used in construction the report [17] does not quantify the material use and related embodied carbon for construction sector.

According a top-down analysis done by Giesekam at al. [18, 19, 20], the total embodied carbon over the last decade from UK construction is quite constant (Fig. 2). This analysis includes main material categories such as Cement&Concrete, Timber, Plastic&Chemicals, Steel&Other Metals, Bricks&Ceramic, Glass and Other (Fig. 3), but does not disaggregate their end use either for new buildings and refurbishment projects or final application.

[1]Cementitious materials include cement and Supplementary Cementitious Materials (SCM) such as Ground Granulated Blast-furnace Slag (GGBS) and Fly Ash (FA)

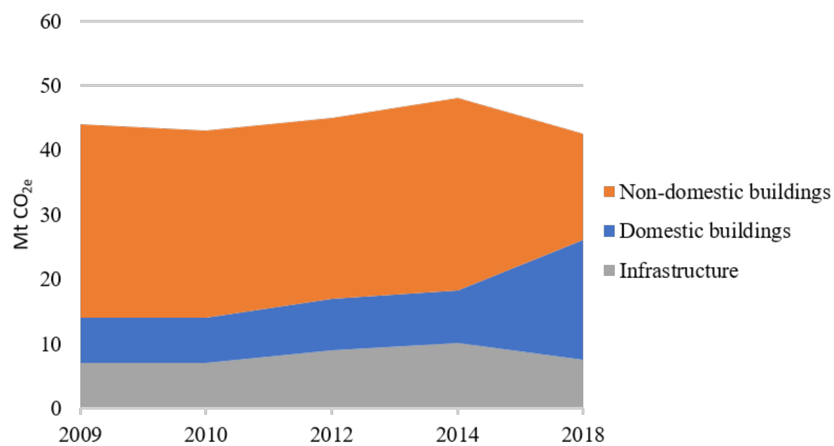


Figure 2: Top-down estimations of embodied carbon in UK construction (2009-2018) [18, 19, 20]

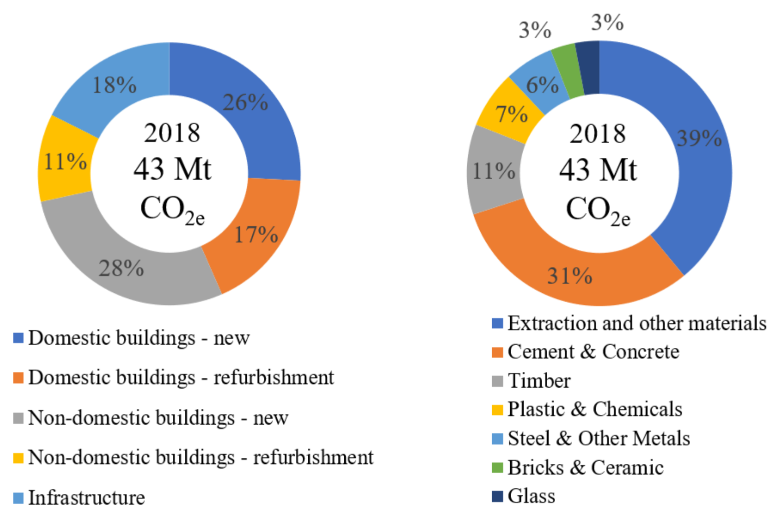


Figure 3: Total embodied carbon share by sector (left), by materials (right) in 2018 [20]

3 Domestic building models used for analysis

Over the last 50 years, the English proportion of domestic building stock was between 83-84% of the UK total, which is identical to the population percentage [8, 21]. When the data for the UK housing sector is unavailable, a good approximation is to use housing statistics for England are scale them up by population.

According to the 2019 English Housing Survey [8], approximately 250 thousand new domestic buildings were competed in 2018 (210 thousand in England [8]), 42 thousand were converted to domestic purposes (36 thousand in England [8]). Terraced houses had the largest share in annual additions to the domestic building stock (33.5%, 2013-2018 average, half end-terraces and half mid-terraced, Table 2) followed by semi-detached houses and low rise purpose-built flats (up to 6 storeys) at 28.5% and 9.3% respectively. The lowest share in annual additions were high rise purpose-built flats (of more than 6 floors) with a share of less than 1%.

The domestic building typologies in this study are modelled in line with those listed in the 2019 English Housing Survey (EHS) [8]. They include end-terrace (E-T), mid-terrace (M-T), detached (D), semi-detached (S-D), bungalow (B), low rise purpose flats (LRF) and high rise purpose flats (HRF). The case studies for modeling each of them were selected to correspond to the average floor space of the different typologies [8]. The identified properties had either 2 or 3 bedrooms (Section 3). The EHS [8] distinguishes low rise buildings (up to six storeys) and high rise residential buildings (above six storeys). However, due to different

Table 1: Typologies reported in English Housing Survey (EHS) [8] and model buildings

Typology	Code	EHS [8] average GIA m^2	Model buildings	Floor area (GIA) m^2	Notes	Figure
End-terrace	E-T	89	3 bedroom	79 [1]	—	Figure 4
Mid-terrace	M-T	88	3 bedroom	79 [2]	End-terrace adjusted to Mid-terrace	Figure 4
Semi-detached	S-D	97	3 bedroom	94[3]	—	Figure 5
Detached	D	149	4 bedroom	132[4]	—	Figure 6
Bungalow	B	77	3 bedroom	76[5]	—	Figure 7
Converted flat	C-F	66	2 bedroom	62	analogy to Purpose built flat	Figure 8
Purpose built flat low rise up to 4 storeys	LRF<4	58	2 bedroom	62[6]	—	Figure 8, 9
Purpose built flat low rise up to 6 storeys	4≤LRF≤6	58	2 bedroom	62	analogy to LRF<4 adjusted to the height*	Figure 8, 9
Purpose built flat high rise up to 10 storeys	7≤HRF≤10	61	2 bedroom	62	analogy to LRF<4 adjusted to the height*	Figure 8, 9
Purpose built flat high rise above 10 storeys	HRF>10	61	2 bedroom	62	analogy to LRF<4 adjusted to the height*	Figure 8, 9

[1] Source: OnTheMarket [22], assessed 05/06/2021
[2] Source: OnTheMarket [22], assessed 05/06/2021
[3] Source: PrimeLocation [23], assessed 10/06/2021
[4] Source: rightmove [24], assessed 28/07/2020
[5] Source: Arnolds Keys [25], assessed 05/05/2021
[6] Source: OnTheMarket [26], assessed 01/04/2021
[*] see Tables 4 - 6

Table 2: Share of net additions - average for five years from 2013-2018 [8]

	Share of net additions by number	Share of net additions by floor area used for demolitions
E-T	16.6%	16.5%
M-T	16.9%	16.7%
S-D	28.5%	31.1%
D	8.9%	14.9%
B	2.1%	1.8%
CF	14.7%	10.9%
LR<6	9.3%	6.1%
4≤LRF≤6	2.3%	1.5%
7≤HRF≤10	0.5%	0.3%
HRF>10	0.1%	0.0%

technology contribution, these categories were divided into 2-4 and 5-6 storeys for low rise buildings and 7-10 and over 10 for high rise residential buildings. Selected case studies represent current housing trends. They were found in early of 2021 on the websites of letting agencies or developers (Section 3). The height of the analysed case studies are typical for houses and bungalows (Annex Table 1.2: Number of storeys above ground by dwelling type [8]) where 90% of typical houses in England were 2 storeys. For each case study, based on the layout, dimensions for the substructure, structure, roof, partitions, cladding, walls and ceiling finishes (e.g. plaster), windows and doors were assumed. The analysis excludes thermal insulation. For each element, the most typical technologies used in the UK were assumed based on NHBC Standards 2021 [27] (Section 3). They were also confirmed as accurate by industry partners with specific, relevant knowledge. The material intensities for different technologies (e.g. cavity walls or timber frames) were modelled based on NBC Standards, structural calculations, guidelines and current practice. For each building typology, the proportions of each viable building technology were assumed.

The case studies represent simply shaped buildings. We have therefore included an allowance for shape irregularity. Which can cause up to 23% carbon inefficiency (material wastage) in floor structures for non-domestic buildings [28]. For this study we have assumed a 10-15% inefficiency allowance for floors and roofs, 5-20% for foundations, ground floors, and partitions, and 5-10% for load bearing walls. A detailed list is included in Section 6.

The material intensity for residential properties includes a 5% material provision for shared space (these might include entrance space, corridors, maintenance rooms, service rooms). Based on the information provided by industry partners, it was also assumed that 20% of single and double family houses and 30% of multi-storey buildings have retaining walls.

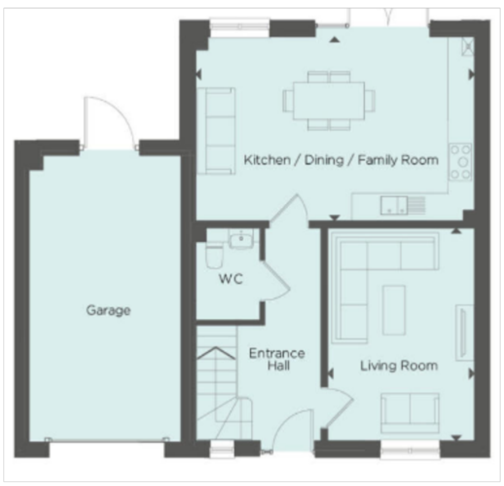
The analysis also includes conversion from office, agricultural, storage and light industrial to residential flats, with the required materials to do this based on the purpose-built flat typology (Table 1, LRF<4). A key driver of conversion from non-domestic to residential purposes is to keep as much existing structure as possible, and it has been reported that 70% structural retention is typical for conversion of non-domestic buildings in London [29]. For this study we assumed that foundations and floor slabs are 100% reused, and 50% of the structural system (load bearing walls, frame). The remaining elements were assumed to be new.

Rooms Kitchen/Dining Area	4.72m x 2.87m
Living Room	4.26m x 3.69m
Bedroom 1	2.96m x 2.83m
Bedroom 2	3.30m x 2.63m
Bedroom 3	3.30m x 2.00m
Total floor Area	79.2m^2

Figure 4: Model of End-terraced house used for this study [22]. Mid-terraced house model has been adapted from End-terraced house by inclusion a half of materials used to create a gable wall and a half of foundations below this wall.

Living Room	5.69m x 3.34m
Dinning / Kitchen	4.79m x 3.30m
Bedroom 1	3.66m x 3.30m
Bedroom 2	3.34m x 3.23m
Bedroom 3	3.34m x 2.37m
Total floor Area	94.90m^2

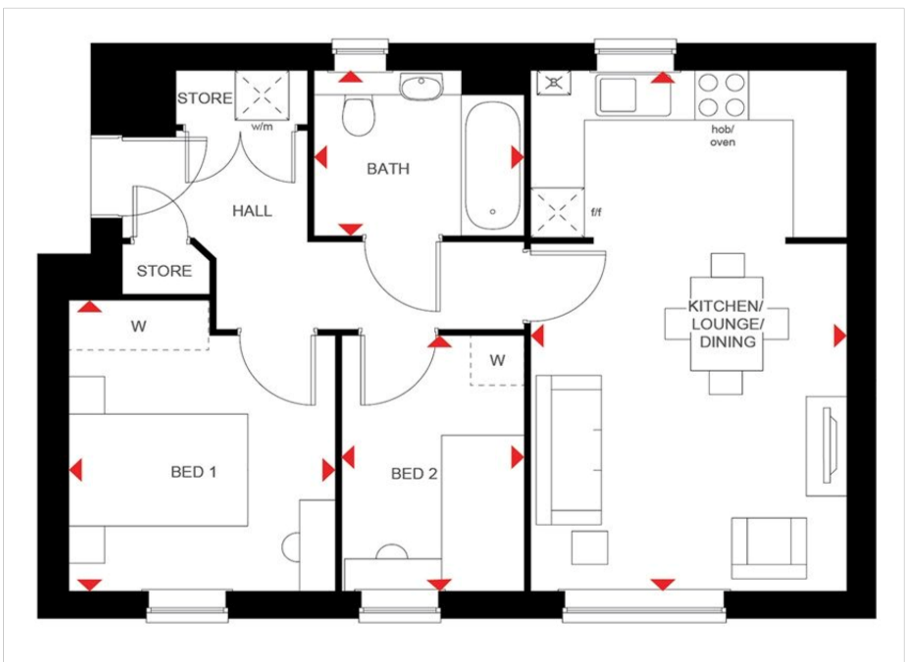
Figure 5: Model of Semi-detached house used for this study [23].



Living Room	4.60m x 3.25m
Dinning / Kitchen	3.95m x 6.25m
Bedroom 1	4.25m x 3.55m
Bedroom 2	4.75m x 2.75m
Bedroom 3	3.15m x 4.00m
Bedroom 4	3.50m x 2.15m
Total floor Area	132.00m^2

Figure 6: Model of Detached house used for this study [24].

Figure 7: Model of Bungalow house used for this study [25].



Kitchen / Lounge	3.08m x 2.03m
Bedroom 1	3.51m x 2.98m
Bedroom 2	2.01m x 2.34m
Total floor Area	62.22m^2

Figure 8: Model of residential building used for this study. The building include 2 flats per floor: flat 1 - Ambersham, flat 2 - Maldon [26]. Foundations and floor plan on Figure 9. The building was adjusted to different heights: 4≤LRF≤6, 7≤HRF≤10, HRF>10 by using provisions included in Tables 4, 5 and 6.

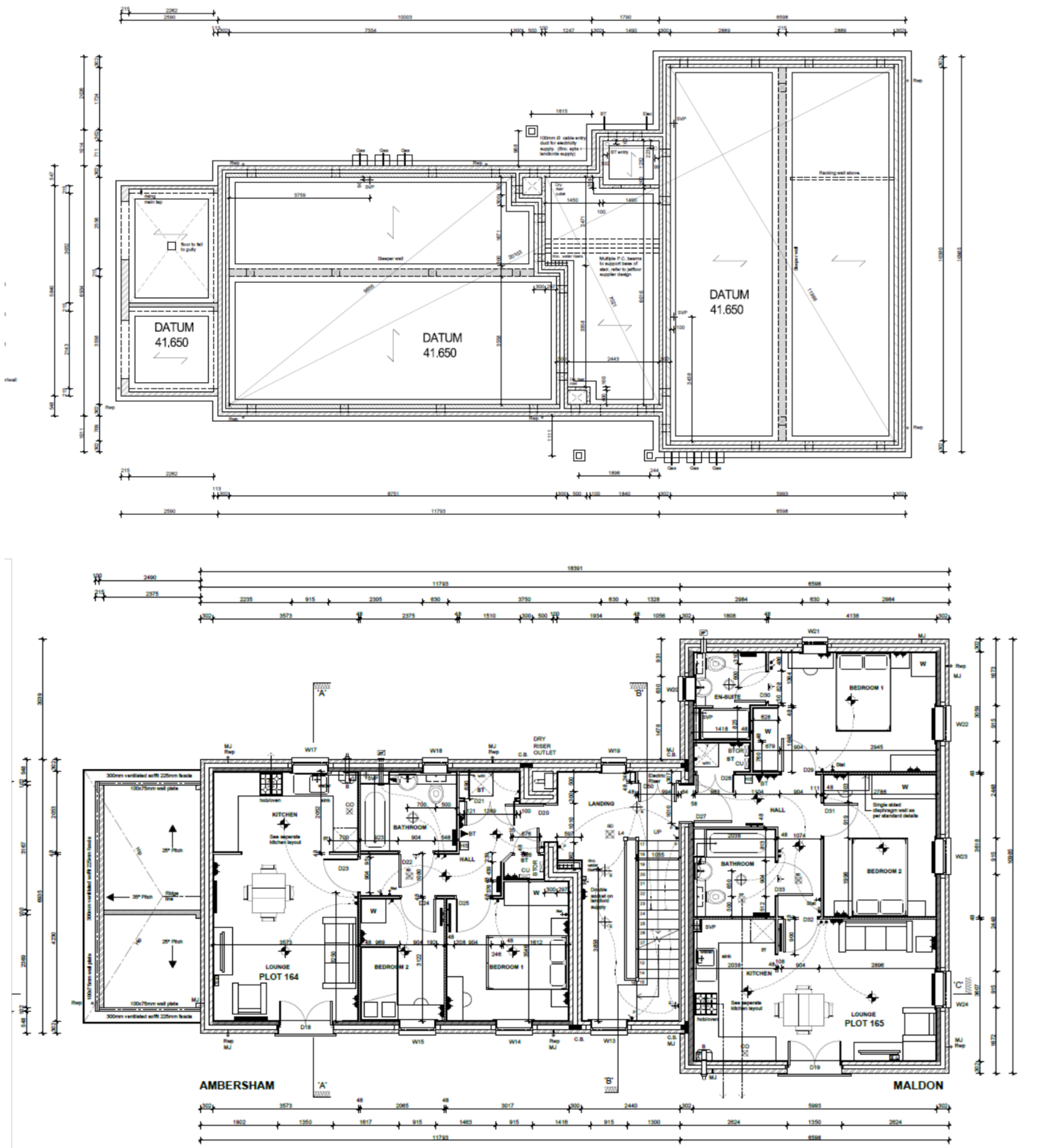


Figure 9: Model of residential building used for this study. The building include 2 flats per floor: flat 1 - Ambersham, flat 2 - Maldon. The building was adjusted to different heights: $4 \leq LRF \leq 6$, $7 \leq HRF \leq 10$, $HRF > 10$ by using provisions included in Tables 4, 5 and 6.

3.1 Material assumptions for calculations and technology shares

Table 3: Technologies used to model domestic building construction.

Element	**Technology**	**E-T, M-T, S-D, D, B**	**C-F**	**LRF<4**	**4≤LRF≤6**	**7≤HRF≤10**	**HRF>10**
Foundations	Concrete strip foundations	80%	n/a	—	—	—	—
	Concrete piles, caps	15%	n/a	50%	40%	20%	80%
	Concrete raft	—	n/a	—	—	60%	20%
	Concrete pad foundations	5%	n/a	50%	60%	20%	—
Ground floor slab	Concrete slab	40%	80%	80%	90%	100%	100%
	Precast beams and concrete blocks	60%	20%	20%	10%	—	—
Structural system	Cavity wall (concrete blocks)	80%	80%	80%	—	—	—
	Cavity wall (clay blocks)	—	—	—	—	—	
	One leaf wall (clay blocks)	—	—	—	—	—	—
	One leaf wall (clay bricks)	—	—	—	—	—	—
	Steel frame - hot rolled sections	1%	1%	1%	10%	10%	10%
	Concrete Frame	—	—	—	20%	40%	40%
	Cold rolled sections frame	—	—	—	40%	40%	40%
	Precast concrete flat panels	—	—	19%	30%	10%	10%
	Timber frame	19%	19%	—	—	—	—
	One leaf wall (clay bricks)	—	—	—	—	—	—
External wall finishing	Bricks (no render)	80%	30%	30%	25%	20%	—
	Bricks (render)	5%	10%	10%	5%	5%	—
	Metal cladding	—	15%	15%	30%	60%	60%
	Concrete cladding	—	15%	15%	15%	15%	40%
	Stone blocks	5%	—	—	—	—	—
	Render (on wall)	3%	10%	10%	10%	—	—
	Timber	5%	15%	15%	10%	—	—
	Brick slips	2%	5%	5%	5%	—	—
Floor structure	Timber (beams, boards)	60%	n/a	20%	—	—	—
	Precast concrete slab with topping	40%	n/a	40%	40%	10%	5%
	Composite deck	—	n/a	—	30%	20%	5%
	Reinforced concrete flat slab	—	n/a	40%	30%	70%	90%
Roof structure	Timber (truss structure)	60%	20%	20%	0%	—	—
	Precast concrete slab with topping	40%	40%	40%	40%	5%	5%
	Composite deck	—	—	—	30%	30%	5%
	Reinforced concrete flat slab	—	40%	40%	30%	70%	90%
Partitions	Timber	40%	30%	30%	20%	—	—
	Precast flat panels	—	—	—	5%	—	—
	Concrete blocks	60%	70%	70%	50%	—	—
	Clay blocks	—	—	—	—	—	—
	Cold rolled sections frame	—	—	—	25%	100%	100%
Roof finishing	Concrete tiles	30%	7%	7%	—	—	—
	Clay tiles	30%	7%	7%	—	—	—
	Natural tiles	30%	6%	6%	—	—	—
	Flat roof	10%	80%	80%	100%	100%	100%
External doors	PVC	60%	20%	20%	20%	20%	20%
	Wooden	20%	20%	20%	20%	20%	20%
	Steel	10%	20%	20%	20%	20%	20%
	Aluminium	—	—	—	—	—	—
	Laminated	10%	40%	40%	40%	40%	40%
Internal doors	Wooden	50%	60%	60%	100%	100%	100%
	Laminated	50%	40%	40%	—	—	—
Windows	PVC	90%	95%	95%	100%	100%	100%
	Wooden	10%	5%	5%	—	—	—
	Aluminium	—	—	—	—	—	—
Inner wall finishing	Cement plaster	Assumed as finishing on all concrete surfaces and walls from blocks					
	Plasterboard	Assumed for timber, steel framed walls and ceilings					
	Gypsum plaster	Assumed on plasterboard and on the top of cement plaster					

Table 4: Specific material quantities for analysed elements Part 1/3

Element	Technology	E-T, M-T, S-D, D, B	C-F	LRF<4	4≤LRF≤6	7≤HRF≤10	HRF>10
Foundations	**Concrete strip foundations**						
	Size [m]	0.6x0.45	n/a	1.0x0.8	LRF<4+15%	LRF<4+25%	LRF<4+35%
	Reinforcement [kg/m^3]	100	n/a	70			
	Concrete	C28/35	n/a	C28/35			
	Notes	For E-T, M-T, S-D, D, B assumed 50% unreinforced					
	Concrete piles, caps						
	Pile size ϕ x H [m]	0.15x4.0	n/a	0.4x4.0	LRF<4+15%	LRF<4+25%	LRF<4+35%
	Reinforcement [kg/m^3]	90	n/a	90			
	Concrete	C28/35	n/a	C28/35			
	Caps size [m]	0.6x0.6x0.4	n/a	1.0x1.0x0.6	LRF<4+15%	LRF<4+25%	LRF<4+35%
	Reinforcement [kg/m^3]	90	n/a	100			
	Concrete	C28/35	n/a	C28/35			
	Notes	4 piles per cap, pile depth 4 m					
	Concrete pile raft						
	Raft depth [mm]	200	n/a	300	LRF<4+15%	LRF<4+25%	LRF<4+35%
	Raft reinforcement [kg/m^3]	90	n/a	110			
	Concrete	C28/35	n/a	C28/35			
	Pile size ϕ x H [m]	0.15x4.0	n/a	0.4x4.0	LRF<4+15%	LRF<4+25%	LRF<4+35%
	Reinforcement [kg/m^3]	90	n/a	90			
	Concrete	C28/35	n/a	C28/35			
	Notes	0.2 piles per m^2 of raft					
	Concrete pads						
	Size [m]	0.4x0.4x0.6	n/a	0.8.0.8x1.0	LRF<4+15%	LRF<4+25%	LRF<4+35%
	Reinforcement [kg/m^3]	110	n/a	110			
	Concrete	C28/35	n/a	C28/35			
Ground floor slab	**Concrete slab**						
	Depth [mm]	150					
	Reinforcement [kg/m^2]	17.8					
	Concrete	C20/25					
	Notes	mesh A252 on the top and bottom (3.95 kg/m^2 x 2) allowance for overlaps 10%					
	Beam and block						
	Beams	Prefab pre-stressed concrete beams, h=175 mm, every 500 mm					
	Reinforcement	4ϕ6 each, 2.66 kg/m^2					
	Concrete	C35/40					
	Blocks	440x215x100mm, 10 blocks per m^2 of floor					
Structural system	**Cavity wall**						
	Concrete blocks	440x215x100mm, 10 blocks per m^2 of wall					
	Cement mortar	0.01 m^3/m^2 of wall, sand:cement ratio - 3:1, density 2080 kg/m^3					
	Clay blocks	300x100x224mm, 14.9 blocks per m^2 of wall					
	Cement mortar	0.01 m^3/m^2 of wall, sand:cement ratio - 3:1, density 2080 kg/m^3					
	One leaf wall						
	Clay blocks	365x248x249mm, 16 blocks per m^2 of wall					
	Cement mortar	0.01 m^3/m^2 of wall, sand:cement ratio - 3:1, density 2080 kg/m^3					
	Clay bricks	215x102.5x65mm, 120 bricks per m^2 of wall					
	Cement mortar	0.01 m^3/m^2 of wall, sand:cement ratio - 3:1, density 2080 kg/m^3					
	Steel frame - sections						
	Weight [kg/m^2]	30	20	40			50
	Notes	Weight from “Cost of structural steelwork” [30]					
	Concrete Frame						
	Concrete volume [m^3/m^2]	0.4 m^3/m^2 of floor area					
	Notes	include only beams and columns, calculated using “Concept V4” [31] modelled as two-way slab, regular grid, 5x5 m					
	Cold rolled sections frame						
	Weight [kg/m^2]	10 kg/m^2 of wall area					
	Notes	Calculated according to “Load Bearing Solutions” [32]					
	Precast concrete flat panels						
	Thickness [mm]	200					
	Reinforcement [kg/m^3]	80					
	Concrete	C32/40					
	Timber frame						
	Weight [kg/m^2]	14.6 kg/m^2 of wall area					
	Notes	Assumed as closed panel timber frame system used for external wall construction in the UK [33]					

Table 5: Specific material quantities for analysed elements Part 2/3

Element	Technology	E-T, M-T, S-D, D, B	C-F	LRF<4	4≤LRF≤6	7≤HRF≤10	HRF>10
Retaining walls	Thickness [mm]	200	n/a	250	LRF<4+5%	LRF<4+10%	LRF<4+15%
	Reinforcement [kg/m^2]	70	n/a	100			
	Concrete	C28/35	n/a	C30/37			
	Notes	height 3.0 m, foot length 2.0 m, assumed that 20% of E-T, M-T, S-D, D, B and 30% of LRF<4, 4≤LRF≤6, 7≤HRF≤10 and HRF>10 have retaining walls					
Lift shafts	Concrete walls	200 mm, C30/37, reinforcement 80 kg/m^3					
	Notes	Assumed lift shaft with internal dimensions 2.0 x 2.0 m					
External wall finishing	**Bricks (no render)**	215 x 102.5 x 65 mm, 60 bricks/m^2					
	Cement mortar	0.02 m^3/m^2 of wall, sand:cement ratio - 3:1, density 2080 kg/m^3					
	Bricks (render)	215 x 102.5 x 65 mm, 60 bricks/m^2					
	Cement mortar	0.02 m^3/m^2 of wall, sand:cement ratio - 3:1, density 2080 kg/m^3					
	Cement plaster	0.01 m^3/m^2, sand:cement ratio - 4:1, density 2040 kg/m^3					
	Metal cladding						
	Weight [kg/m^2]	7.71 kg/m^2 of wall					
	Notes	100 mm steel panel, 0.5/0.5 mm, only steel [34]					
	Concrete cladding						
	Thickness [mm]	100					
	Concrete	C35/40					
	Notes	Fibre reinforced concrete, fibres not included					
	Stone blocks	200 x 100 x 65 mm, 50 bricks/m^2					
	Cement mortar	0.02 m^3/m^2 of wall, sand:cement ratio - 3:1, density 2080 kg/m^3					
	Notes	Traditional 100 mm blocks [35]					
	Render (on wall)						
	Cement plaster	0.01 m^3/m^2, sand:cement ratio - 4:1, density 2040 kg/m^3					
	Timber						
	Thickness [mm]	20					
	Brick slips						
	Thickness [mm]	15					
	Cement mortar	0.01 m^3/m^2 of wall, sand:cement ratio - 3:1, density 2080 kg/m^3					
Floor structure	**Timber (beams, boards)**						
	Structure	Beams 47x175 mm every 400mm, floor board 22x150 mm					
	Weight [kg/m^2]	21.3 kg/m^2 of floor					
	Precast concrete slab						
	Precast slab	150 mm, C40/50, reinforcement 30 kg/m^3					
	Topping	100 mm, C32/40, reinforcement 90 kg/m^3					
	Composite deck						
	Steel deck	12.45 kg/m^2					
	Concrete slab	concrete 0.1 m^3/m^2, reinforcement 25 kg/m^3					
	Reinf. concrete flat slab						
	Slab	200 mm, C30/37, reinforcement 60 kg/m^3					
Roof structure	**Timber (truss structure)**						
	Weight [kg/m^2]	19 kg/m^2 of roof					
	Notes	Standard roof truss, truss centres 600 mm, timber thickness 35 mm, calculated according to [36]					
	Precast concrete slab						
	Precast slab	150 mm, C40/50, reinforcement 30 kg/m^3					
	Topping	100 mm, C32/40, reinforcement 90 kg/m^3					
	Composite deck						
	Steel deck	12.45 kg/m^2					
	Concrete slab	concrete 0.1 m^3/m^2, reinforcement 25 kg/m^3					
	Reinf. concrete flat slab						
	Slab	200 mm, C30/37, reinforcement 60 kg/m^3					
Roof finishing	**Concrete tiles**	60 kg/m^3, 21 tiles per m^2 [37, 38]					
	Clay tiles	80 kg/m^3, 70 tiles per m^2 [37, 38]					
	Natural tiles	40 kg/m^3, 40 tiles per m^2 [37, 38]					

Table 6: Specific material quantities for analysed elements Part 3/3

Element	Technology	E-T, M-T, S-D, D, B	C-F	LRF<4	4≤LRF≤6	7≤HRF≤10	HRF>10
Partitions	**Timber**						
	Weight [kg/m^2]	9.85 kg/m^2 of wall area					
	Notes	Assumed as an open panel timber frame system used in the UK [39]					
	Precast flat panels						
	Thickness [mm]	100					
	Reinforcement [kg/m^3]	70					
	Concrete	C32/40					
	Concrete blocks						
	Concrete blocks	440x215x100mm, 10 blocks per m^2 of wall					
	Cement mortar	0.01 m^3/m^2 of wall, sand:cement ratio - 3:1, density 2080 kg/m^3					
	Cold rolled sections frame						
	Weight [kg/m^2]	5.3 kg/m^2 of wall area					
	Notes	Calculated according to “Load Bearing Solutions” [32]					
External doors	**PVC**	PVC frame 8.6 kg/m^2 of door [40]					
	Wooden	Wooden frame and wooden leaf 17.7 kg/m^2 of door [41]					
	Steel	Steel frame and steel leaf 33.4 kg/m^2 of door [42]					
	Laminated	Steel frame and laminated leaf 19.3 kg/m^2 [42]					
	Notes	Glass - assumed 5% of door surface double glass - 5 mm glass / 20 mm cavity / 5 mm glass glass weight 25 kg/m^2					
Internal doors	**Wooden**	Wooden frame and wooden leaf (softwood) 17.7 kg/m^2 of door [41]					
	Laminated	Steel frame and steel leaf 33.4 kg/m^2 of door [42]					
Windows	**PVC**	PVC frame 8.6 kg/m^2 of window [40]					
	Wooden	Wooden frame 31.6 kg/m^2 of window [41]					
	Aluminium	Assumed 7.1 kg of aluminium profile per m^2 of window [43]					
	Notes	Glass - assumed 75% of window surface double glass - 5 mm glass / 20 mm cavity / 5 mm glass glass weight 25 kg/m^2					
Inner wall finishing	**Cement plaster**	Assumed as finishing on all concrete surfaces and walls from blocks 0.01 m^3/m^2, sand:cement ratio - 4:1, density 2040 kg/m^3					
	Plasterboard	Assumed for all timber, steel framed walls and ceilings 12.7 mm, 6.3 kg/m^2					
	Gypsum plaster	Assumed on plasterboard and on the top of cement plaster 2 mm, density 920 kg/m^3					

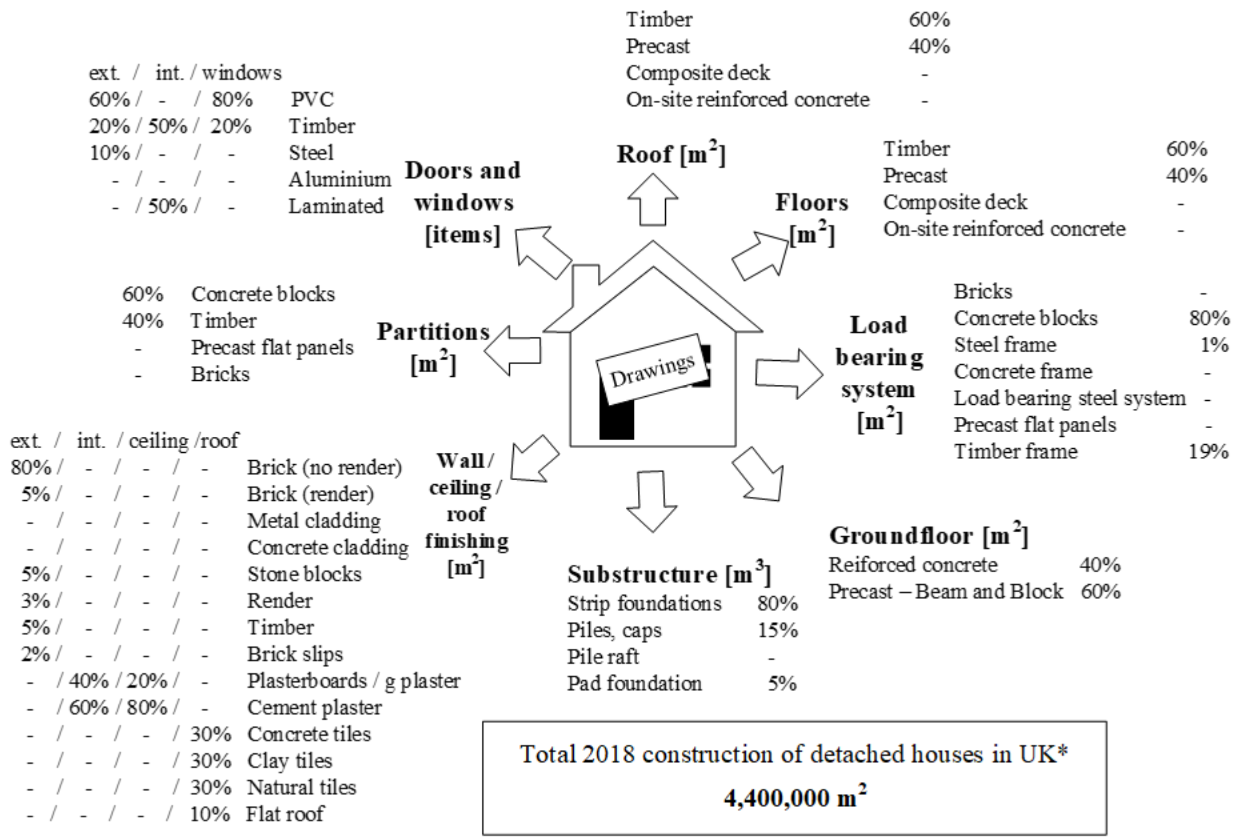


Figure 10: Example of material use for detached house (D) - the same methodology was used for other domestic buildings as well as non-residential buildings.

* typologies share - five year net additions share of typologies in England (2013-2018), scaled by population to cover the UK

4 Non-domestic building models used for analysis

The Valuation Office Agency (VOA) [44] publish an annual report titled "Non-domestic rating: stock of properties including business floorspace", which includes the number and floorspace of rateable properties in England and Wales. A rateable property is a unit of property that is, or may become, liable to non-domestic rating and thus appears in a rating list. These statistics are broken down into Retail, Office, Industrial and Other categories. Table 7 presents the sectors and sub-sectors included in "Non-domestic rating" as well as assumed typologies.

In 2018 in England and Wales there were 2.1 m non-domestic properties. 25% were Retail (RB), 25% Industrial (IB), 20% Office (OB) and 30% Other (O). Non-domestic stock floor area was 587 m m^2, 54.9% of which represented IB, 17.7% RB, 16.8% OB and 10.6% other [44]. Scaled to the UK population, the number of non-domestic buildings can be estimated as 2.3 m (660 m m^2). Compared to 2017, net-addition of non-domestic rateable properties in 2018 was 60 thousand (2.7 m m^2). Net-addition was positive in both number and floor area for Retail, Industrial and Other categories, but for Offices the floor area net-addition was negative despite the number being positive.

For this study, two office buildings and three industrial buildings were modelled. For the Retail sector, a combination of office and industrial buildings was assumed. Due to wide variety of buildings included in the "Other" sector (Table 7), a material intensity per m^2 was assumed as an average from all materials calculated for domestic buildings, retail, office and industrial buildings. Further details of these non-domestic typologies are given in the sections which follow.

Table 7: Sector and sub-sector categories of non-domestic buildings [44]

Sector	**Sub-sector**	**Typologies**
Office (OB)	Offices	Low Rise (OLR) High Rise (OHR)
Industrial (IB)	General Industrial Storage & Distribution Other	Small Industrial unit (SIU) Medium industrial unit (MIU) Large industrial unit (LIU)
Retail (RB)	Financial and Professional Services Shops	Financial and Professional Services (FPS) Shops (S)
Other (O)	Assembly and Leisure Education Health Hotels, Guest & Boarding, Self-Catering etc. Non Residential Institutions Retail (other than above) Residential Institutions Storage & Distribution Transport Utilities Offices (part of a specialist property) Other(not listed above)	Other buildings (O)

4.1 Office buildings (OB)

In November 2011 the BCSA and Tata Steel commissioned Gardiner & Theobald (G&T), Peter Brett Associates (PBA) and Mace Group to undertake an impartial study of current construction practice for multi-storey offices to provide cost and programme guidance for quantity surveyors and design. The study included two representative building types at either end of the range for commercial office development [45].

- Office Building 1 (OLR) – Business Park office building, 3 storeys, 3,000m^2 GIA, structural grid 7.5 – 9m,
- Office Building 2 (OHR) – City centre office building, 8 storeys, 15,000m^2 GIA, structural grid 7.5 – 15m.

Table 8: Office buildings - Framing options from the cost study included in [45]

Low Rise (OLR) office building 7.5 x 9m grid
Steel composite beams and composite slab Steel frame and non-composite precast concrete floor
Reinforced concrete flat slab
Reinforced concrete flat slab
Post-tensioned band beams, and PT slab
High Rise (OHR) office building 7.5 x 15m grid
Cellular/Plate girder composite beams and composite slab
Conventional steel UB's with composite slab with discrete holes
Post-tensioned band beams, and PT slab, in-situ columns

PBA designed these buildings in the UK's most commonly used technologies (Table 8). Key design assumptions are included Table 9. 4 different framing options for the Office Building 1 (OLR), and three for the Office Building 2 (OHR) (Table 10) were assumed. Material quantities in this study were used from PBA take-offs. No information exists on the share of technologies and the share or low/medium/high office buildings in the UK. The shares adopted for this study are presented in Table 10.

For this study, the share of technologies were assumed and verified by industrial partners (Table 10). After Dunant at al. [28], allowances were made for real-word irregular grids and structure inefficiencies, 10-30% for floors and roofs, 5-30% for foundations, ground floor, and partitions, 5-10% load bearing walls (Section 6).

The width of the floorplate for Office Building 1 (OLR) has been set at 18 m, which is commonly used because it lends itself to open plan office space. It is suitable for mixed mode mechanical ventilation and facilitates natural light ingress to some of the floorplate, especially where a central corridor is used. The grid of building 1 has been set at 7.5 x 9m, assuming two bays of 9 m across the 18 m floorplate and 7.5 m perimeter spacing (Figure 11).

The grid of Office Building 2 (OHR) has been set at 7.5 x 15 m, assuming a single 15 m bay across the floorplate and 7.5 m perimeter column spacing. The grid was assumed as the most representative of conventional office arrangements. The 7.5 m grid coordinates with car parking bays if these were to be incorporated into the ground floor or basement of an office building (Figure 12). Any retail or reception space at ground floor was assumed to fit within the typical grid layout.

Table 9: Design assumptions

Item	Office Building 1 (Low rise, OLR)	Office Building 2 (High Rise, OHR)
Height	3 storeys, storey height 2.8 m	8 storeys, storey height 3.0 m
GIA	3,000 m^2 GIA	15,000m^2
Grids	7.5 x 9 m	7.5 x 15 m
Dead loads	Self-weight	
Superimposed dead loads	0.85 kN/m^2	
Imposed loads	4.0 kN/m^2 (+1 kN/m^2)	
Deflections	Imposed load deflection -Span/360 Total deflection - span /200 and 60 mm at bay center Edge deflections - 10 mm Edge deflections - 10 mm Span/depth ratio - is L/18 Precamber where required.	Imposed load deflection - span/360 Total deflection - span /200. Edge deflections - 10 mm Span/depth ratio - is L/18 Precamber where required.
Vibration	Response factor of 8, Slab thicknesses to EC2 [46, 47]	
Core Construction	Steel cross braced or Concrete Core Walls	Concrete Core Walls
Floor heights	Floor to ceiling height 2.8 m Ceiling and lighting zone 150 mm Raised floor zone 150 mm	Floor to ceiling height 3.0 m Ceiling and lighting zone 150 mm Raised floor zone 200 mm
Fire	$\frac{1}{2}$ hour and is not sprinklered on-site intumescent to steel, boarding to columns	1 hour with sprinklers on-site intumescent to steel, boarding to columns
M&E	Mixed mode with natural ventilation. 300mm deep ceiling void below the structure	Conventional fan coil air conditioning, without natural ventilation. 400mm deep ceiling void below concrete structure or integrated into the steel zone
Finishes	Raised floor 150 mm deep	Raised floor is 200 mm deep
Partitions	Core walls blockwork Internal partitions metal stud	Core walls concrete Internal partitions metal stud
Cladding	Cavity brick/METSEC construction	Conventional curtain wall system
Roof	Lightweight roof for steel options, concrete slab for concrete options. 5% gross plant area with 50% enclosed plantroom area	7.5% gross roof plant area, with 50% being enclosed plantroom
Foundations	Medium dense sand Unreinforced mass concrete pads*	London clay CFA piles with option for steel bearing piles
Materials	Steelwork S355 throughout Concrete C40 throughout Reinforcement 500 N/mm^2	Steelwork S355 throughout Concrete C40 slabs, C50 columns Reinforcement 500 N/mm^2 Lightweight concrete where appropriate
Codes	EC2/EC3 [46, 47, 48, 49]	

* Assumed a half of concrete pads unreinforced.

Figure 11: Model of low-rise Office building used for this study [45]

Table 10: Framing options for the cost study included in [45]

	Low Rise (OLR) 7.5 x 9m grid	Assumed share within the group	Assumed share within the “Office” office
Ia	Steel composite beams and composite slab	30%	70%
IIa	Steel frame and non-composite precast concrete floor	30%	
IIIa	Reinforced concrete flat slab	30%	
IVa	In-situ concrete frame with post tensioned slab	10%	
	High Rise 7.5 x 15m grid	Assumed share within the group	Assumed share within the “Office”
Ib	Cellular/Plate girder composite beams and composite slab	15%	30%
IIb	Conventional steel UB’s with composite slab with discrete holes	40%	
IIIb	Post-tensioned band beams, and PT slab, in-situ columns	45%	

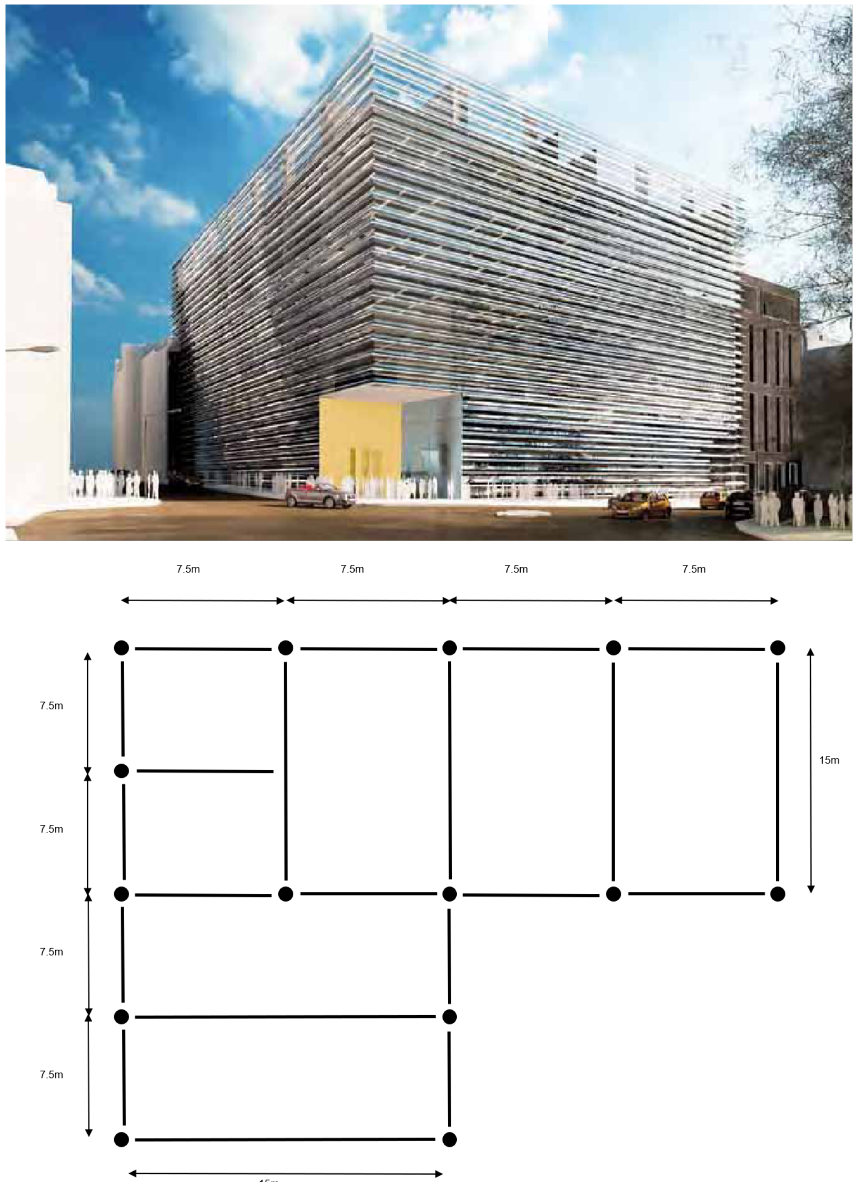


Figure 12: Model of mid-rise Office building used for this study [45]

Table 11: Material intensity for Office Building 1 (OLR), Part 1/2

Element	**Ia**	**IIa**	**IIIa**	**IVa**
Structural Foundation				
Deep foundation slab / Pads[a] [m^3]	273.7	312.4	521.3	441.5
Reinforcement[b] [kg/m^3]	100			
Concrete[a]	C32/40			
Ground bearing slab 150 mm[a]	162.8			
Reinforcement[b] [kg/m^3]	60			
Concrete[a]	C32/40			
Retaining walls[c]				
Length of retaining walls[b] [m]	156			
Dimensions [b]	wall: h=4 m, w=0.2 m, foot: w=2.0 m, h=0.2 m			
Reinforcement[b] [kg/m^3]	130			
Concrete[b]	C32/40			
Structural Columns				
Steel sections[a] [t]	25.3	33.4	—	—
Concrete columns[a] [m^3]	—	—	42.6	59.6
Reinforcement[b] [kg/m^3]	—	—	180	
Concrete[a]	—	—	C40/50	
Structural frame (floors)				
Steel sections[a] [t]	81.4	75.0	—	—
Slab				
Slab thickness[a] [mm]	130	250	325	215-275
Steel deck[b] [kg/m^2]	12.4	—	—	—
Reinforcement[b] [kg/m^3]	25.2	15.2	130	94.3
Concrete[a]	C32/40	C40/50	C32/40	
Topping concrete[a] [mm]	—	50	—	—
Reinforcement[b] [kg/m^3]	—	50	—	—
Concrete[a]	—	C32/40	—	—
Roof				
Lightweight roof sections[b] [kg/m^2]	15		—	—
Lightweight roof 124 mm steel panels[b] [kg/m^2]	11.9 (steel [50])		—	—
Slab thickness[b] [mm]	—	—	200	200
Reinforcement[b] [kg/m^3]	—	—	130	94.3
Concrete[a]	—	—	C32/40	

[a] Provided take-offs;
[b] Assumption;
[c] In final calculations assumed that 75% of buildings have retaining walls / basement;

Table 12: Material intensity for Office Building 1 (OLR), Part 2/2

Element	Ia	IIa	IIIa	IVa
Lift shaft				
Number of lift shafts[b] [m]	2			
Dimensions[b] [m]	2.0 x 3.0, wall thickness 0.15			
Reinforcement[b] [kg/m^3]	120			
Concrete[b]	C32/40			
Stairs				
Number of staircases[b]	2			
Dimensions[b] [m]	walls: 4.15 x 2.40 stands: 2.40 x 1.75 steps: 0.25 x 0.20			
Thickness[b][m]	walls: 0.2, stands: 0.2			
Reinforcement[b] [kg/m^3]	150			
Concrete[b]	C32/40			
Façade				
Façade area[d] [m^2]	960			905
Cold rolled sections [kg/m^2]	10 [32]	—	—	—
Concrete blocks[b] [m^3/m^2]	0.10			
Cement mortar[b] sand:cement ratio - 3:1 [m^3/m^2]	0.01			
Cement plaster[b] sand:cement ratio - 4:1 [m^3/m^2]	0.01			
Bricks	215 x 102.5 x 65 mm 60 bricks/m^2			
Cement mortar[b] sand:cement ratio - 3:1 [m^3/m^2]	0.02			
Cement plaster[b] sand:cement ratio - 4:1 [m^3/m^2]	0.01			
Partitions				
Core walls - concrete blocks[b] [m^2]	650			610
Cement mortar[b] sand:cement ratio - 3:1 [m^3/m^2]	0.02			
Cement plaster[b] sand:cement ratio - 4:1 [m^3/m^2]	0.01			
Internal partitions metal studs[b] [m^2]	1265			1190
Cold rolled sections [kg/m^2]	5.3 [32]			
Plasterboard[b]	12.7 mm, 6.3 kg/m^2			
Gypsum plaster[b]	2 mm, density 920 kg/m^3			
Windows				
Area of windows[d] [m^2]	640			600
PVC frame[e] [kg/m^2]	8.6 [40]			
Wooden frame[e] [kg/m^2]	31.6 [41]			
Aluminium frame [kg/m^2]	7.1 [43]			
Glass	assumed 75% of window surface double glass 5 mm glass / 20 mm cavity / 5 mm glass glass weight 25 kg/m^2			
Doors				
Number of external glass doors (aluminium)[b]	3, 3 m (2x1.5 m) x 2.3 m; 20.7 m^2			
Aluminium frame and aluminium leaf (frame)	14 kg/m^2 of door [43]			
Glass	80% of door area			
Number of external steel doors[b]	5, 1.0 x 2.0 m; 6.0 m^2			
Steel frame and steel leaf (steel)	33.4 kg/m^2 of door [42]			
Total area of internal doors[b] [m^2]	110			
Steel frame and laminated leaf (frame)	19.3 kg/m^2 [42]			

[a] Provided take-offs
[b] Assumption
[c] In final calculations assumed that 75% of buildings have retaining walls / basement
[d] Assumed as 60% of all area (allowance for windows and doors 40%)
[e] Assumed that a third of windows are timber, a third PVC and a third aluminium

Table 13: Material intensity for Office Building 2 (OHR), Part 1/2

Element	**Ib**	**IIb**	**IIIb**
Structural Foundation			
Piles D=900 mm[a] [item]	147		150
Depth[b] [m]		10	
Concrete[b]		C32/40	
Reinforcement[b] [kg/m^3]		70	
Pile caps / slab [a] [m^3]	202.0		1 071.5
Concrete[a]		C32/40	
Reinforcement[b] [kg/m^3]		110	
Ground bearing slab 150 mm[a]	316.3	310.4	
Reinforcement[b] [kg/m^3]		60	
Concrete[a]		C32/40	
Retaining walls[c]			
Length of retaining walls[b] [m]		195	
Dimensions [b]		wall: h=4 m, w=0.2 m foot: w=2.0 m, h=0.2 m	
Reinforcement[b] [kg/m^3]		130	
Concrete[b]		C32/40	
Structural Columns			
Steel sections[a] [t]	22.4	23.0	—
Concrete columns[a] [m^3]	—	—	141.0
Reinforcement[b] [kg/m^3]	—	—	150
Concrete[a]	—	—	C40/50
Structural frame (floors)			
Steel sections[a] [t]	144.0	1 120.9	15.5
Fabricated sections[a] [t]	148.8	—	—
Concrete beams (PT)[a] [m^3]	—	—	1 842.2
Reinforcement[b] [kg/m^3]	—	—	120
Concrete[b]	—	—	C40/50
Slab			
Slab thickness[a] [mm]	130	130	225
Steel deck[b] [kg/m^2]	12.4	12.4	—
Reinforcement[b] [kg/m^3]	25.2	25.2	130
Concrete[a]		C32/40	
Roof			
Slab thickness[a] [mm]	130	130	225
Steel deck[b] [kg/m^2]	12.4	12.4	—
Concrete[a]		C32/40	
Lift shaft			
Number of lift shafts[b] [m]		3	
Dimensions[b] [m]		3.0 x 4.0, wall thickness 0.20	
Reinforcement[b] [kg/m^3]		120	
Concrete[b]		C32/40	
Stairs			
Number of staircases[b]		2	
Dimensions[b] [m]		walls: 4.15 x 2.40 stands: 2.40 x 1.75 steps: 0.25 x 0.20	
Thickness[b][m]		walls: 0.2, stands: 0.2	
Reinforcement[b] [kg/m^3]		150	
Concrete[b]		C32/40	

[a] Provided take-offs;
[b] Assumption;
[c] In final calculations assumed that 75% of buildings have retaining walls / basement;

Table 14: Material intensity for Office Building 2 (OHR), Part 2/2

Element	Ib	IIb	IIIb
Façade			
Façade area (curtain wall)[d] [m^2]		7220	8400
Steel curtain wall[e] [kg/m^2]		19 [51]	
Aluminium curtain wall[e] [kg/m^2]		9 [51]	
Glass		80% of surface double glass 5 mm glass / 20 mm cavity / 5 mm glass glass weight 25 kg/m^2	
Walls			
Concrete core walls 200 mm[a] [m^2]		2 425	
Reinforcement[b] [kg/m^3]		75	
Concrete[b]		C32/40	
Cement plaster[b] [m^3/m^2]		0.01	
Partitions[b] [m^2]		3 638	
Cold rolled sections frame[b][kg/m^2]		10 kg/m^2 of wall area [32]	
Plasterboard[b]		12.7 mm, 6.3 kg/m^2	
Gypsum plaster[b]		2 mm, density 920 kg/m^3	
Door			
Number of external glass doors (aluminium)[b]		3, 3 m (2x1.5 m) x 2.3 m; 20.7 m^2	
Aluminium frame and aluminium leaf (frame)		14 kg/m^2 of door [43]	
Glass		80% of door area	
Number of external steel doors[b]		5, 1.0 x 2.0 m; 6.0 m^2	
Steel frame and steel leaf (steel)		33.4 kg/m^2 of door [42]	
Total area of internal doors[b] [m^2]		110	
Steel frame and laminated leaf (frame)		19.3 kg/m^2 [42]	

[a] Provided take-offs;
[b] Assumption;
[c] In final calculations assumed that 75% of buildings have retaining walls / basement;
[d] Assumed curtain wall as 100% of all façade area;
[e] Assumed that a a half of curtain wall is steel frame, a half, aluminium;

4.2 Industrial buildings (IB)

The VOA [44] divide industrial buildings into three sub-categories: General Industrial, Storage & Distribution and Other. For the purpose of this study three industrial buildings of different sizes - small (SIU), medium (MIU) and large (LIU). They were modeled as steel structures with reinforced concrete pad foundations, curtain walls and lightweight sandwich panel roofs. An overview is given in Table 15. This table presents also the assumed shares of each type.

The material intensities for different buildings were taken either directly from the source (e.g. [52] for SIU), used typical material intensity for similar buildings (e.g. steel use per m^2 for MIU and LIU from [53]) or used average material intensity from previous sections. The assumed structural inefficiency allowances were 5-10% for steel elements, 30% for concrete elements (e.g. foundations), and 5-10% for partitions. The material intensities are provided in Tables 16, 17, 18 for SIU, MIU and LIU respectively.

Table 15: Industrial buildings (IB)- case studies

Typology	**Small industrial unit**	**Medium size industrial unit**	**Large size industrial unit**
Code	SIU	MIU	LIU
Source	[52]	[53]	[54]
Number of storeys	1	1	1
Height	4 m	10 m	7 m
GIA	900	5,000	12,000
Shape	rectangle	rectangle	rectangle
Dimensions	50x18 (one main span)	125x40 (2 main spans x 20 m)	150x80 (2 main spans x 40 m)
Share within industrial	50%	30%	20%

4.2.1 Small size industrial unit SIU - adapted from [52]

Small size industrial unit assumes as a single storey new building with a gross internal floor area of 900 m^2, subdivided into five industrial units. It ass Reinforced concrete ground bearing slab and pads to receive a steel portal frame. Wall and roof cladding is aluminium built up system, with internal blockwork division walls. Each of the five units has a separate entrance door and one roller shutter door, together with a single WC. Units vary in size from 150 m^2 to 360 m^2. Model location is South East England.

4.2.2 Medium size industrial unit MIU - adapted from [53]

Medium size industrial unit assumes as a single storey new building with a gross internal floor area of 5,000 m^2. Assumed overall dimensions 40x124 (span: 2x20; 5x25m) with overall height 10m. Assumed reinforced concrete pad foundations, reinforced concrete ground floor, steel portal frame.

All assumptions are included in Table 17.

4.2.3 Large size industrial unit LIU - adapted from [54]

Large size industrial unit (LIU) assumes as a single storey new building with a gross internal floor area of 12,000 m^2. Assumed overall dimensions 80x150 (span: 2x40; 1x25m) with overall height 7m. Assumed reinforced concrete pad foundations, reinforced concrete ground floor, steel portal frame.

All assumptions are included in Table 18.

Table 16: Material intensity for the Small size industrial unit - SIU

Element	SIU
Substructure	
Reinforced concrete ground slab, including ground beams and column bases[a] [m^2]	900
Pad foundations[b] [items]	16
Pad foundations[b] [size]	1.2x1.2x0.6m[d]
Ground slab depth[b] [m]	0.175
Concrete[b]	C32/40
Reinforcement[b] [kg/m^3]	70
Strip foundations for partly walls [m]	80
Size[b] [m]	0.20x0.40
Concrete[b]	C32/40
Reinforcement[b] [kg/m^3]	70
Frame and Upper Floors	
Steel propped portal frame, hot rolled sections, surface treatments (40 kg/m^2)[a] [t]	36
Roof	
Built up aluminium roof cladding with 180 mm thick insulation [a] [m^2]	950[c]
Weight of aluminium cladding (thickness 0.9mm)[c] [kg/m^2]	4.0 [55]
Weight of steel (thickness 0.7mm)[c] [kg/m^2]	6.8 [55]
External Wall, Windows and Doors	
Built up aluminium wall cladding with 130 thick insulation [a] [m^2]	520[c]
Weight of aluminium cladding (thickness 0.9mm)[c] [kg/m^2]	4.0 [55]
Weight of steel (thickness 0.7mm)[c] [kg/m^2]	6.8 [55]
2.5 m high inner leaf of 140 thick fairface blockwork [b] [m^2]	225
Bricks [per m^2]	215 x 102.5 x 65 mm 60 bricks per m^2
Cement mortar [kg/m^2 of the wall]	0.02 m^3/m^2, sand:cement ratio - 3:1, density 2080 kg/m^3
3000 x 4600 mm high steel sectional overhead doors[a] [item]	5
Steel weight per m^2	0.9kg/^{2} [56]
Aluminium weight per m^2	0.45kg/^{2} [56]
Aluminium single entrance doors[a], no glass [item]	5
Size[b] [m]	1.0x2.0
Weight per m^2	21 kg/m^2
Coated aluminum double glazed window system[a] [m^2]	150
Aluminium sections[b] [kg/m^2]	14 kg/m^2 of door [43]
Partitions and Doors	
2 hour fire resistant blockwork party walls [m^2]	450
Block per m^2 of wall[b]	10 blocks/m^2 (440x215x100mm)
Cement mortar per m^2 of wall[b]	0.02 m^3/m^2
Metal stud partitions[a] [m^2]	50
Weight of studs [kg/m^2 of the wall]	5.3 [32]
Laminated faced internal doorset with softwood frames [item]	5
Size[b] [m]	0.9x2.0
Wall finishes (internal walls)	
Cement plaster, sand:cement ratio - 4:1, density 2040 kg/m^3 [m^3/m^2]	0.01

[a] Provided from [52]
[b] Assumptions
[c] Assumed the share of aluminum / steel cladding as 50% / 50%
[d] Assumed 10% allowance for ground beams

Table 17: Material intensity for the Medium size industrial unit - MIU

Element	**SIU**
Substructure	
Pad foundations[a] [items]	41
Pad foundations[a] [size]	1.4x1.4x0.7m[c]
Concrete[a]	C32/40
Reinforcement[a] [kg/m^3]	70
Reinforced concrete ground slab[a] [m^2]	5000
Depth[a] [m]	0.175
Strip foundations for partly walls [m]	170
Size[a] [m]	0.20x0.40
Concrete[a]	C32/40
Reinforcement[a] [kg/m^3]	70
Frame and Upper Floors	
Steel propped portal frame, hot rolled sections, surface treatments (50 kg/m^2)[a] [t]	250
Roof	
Built up aluminium roof cladding with 180 mm thick insulation [a] [m^2]	5275[c]
Weight of aluminium cladding (thickness 0.9mm)[b] [kg/m^2]	4.0 [55]
Weight of steel (thickness 0.7mm)[b] [kg/m^2]	6.8 [55]
External Wall, Windows and Doors	
Built up aluminium wall cladding with 130 thick insulation [a] [m^2]	3234[c]
Weight of aluminium cladding (thickness 0.9mm)[b] [kg/m^2]	4.0 [55]
Weight of steel (thickness 0.7mm)[c] [kg/m^2]	6.8 [55]
2.5 m high inner leaf of 140 thick fairface blockwork [a] [m^2]	290
Bricks [per m^2]	215 x 102.5 x 65 mm 60 bricks per m^2
Cement mortar [kg/m^2 of the wall]	0.02 m^3/m^2, sand:cement ratio - 3:1, density 2080 kg/m^3
3000 x 4600 mm high steel sectional overhead doors[a] [item]	7
Steel weight per m^2	0.9kg/^{2} [56]
Aluminium weight per m^2	0.45kg/^{2} [56]
Aluminium single entrance doors[a], no glass [item]	8
Size[b] [m]	1.0x2.0
Weight per m^2	21 kg/m^2
Coated aluminum double glazed window system[a] [m^2]	50
Aluminium sections[b] [kg/m^2]	14 kg/m^2 of door [43]
Partitions and Doors	
2 hour fire resistant blockwork party walls [m^2]	550
Block per m^2 of wall[a]	10 blocks/m^2 (440x215x100mm)
Cement mortar per m^2 of wall[a]	0.02 m^3/m^2
Metal stud partitions[a] [m^2]	100
Weight of studs [kg/m^2 of the wall]	5.3 [32]
Laminated faced internal doorset with softwood frames [item]	12
Size[a] [m]	0.9x2.0
Wall finishes (internal walls)	
Cement plaster, sand:cement ratio - 4:1, density 2040 kg/m^3 [m^3/m^2]	0.01

[a] Assumptions
[b] Assumed the share of aluminum / steel cladding as 50% / 50%
[c] Assumed 10% allowance for ground beams

Table 18: Material intensity for the Large size industrial unit - LIU

Substructure	
Pad foundations[a] [items]	46
Pad foundations[a] [size]	1.8x1.8x0.8m[c]
Concrete[a]	C32/40
Reinforcement[a] [kg/m^3]	70
Reinforced concrete ground slab[a] [m^2]	12 000
Depth[a] [m]	0.25
Strip foundations for partly walls [m]	170
Size[a] [m]	0.20x0.40
Concrete[a]	C32/40
Reinforcement[a] [kg/m^3]	70
Frame and Upper Floors	
Steel propped portal frame, hot rolled sections, surface treatments (50 kg/m^2)[a] [t]	600
Roof	
Built up aluminium roof cladding with 180 mm thick insulation [a] [m^2]	12 660[c]
Weight of aluminium cladding (thickness 0.9mm)[b] [kg/m^2]	4.0 [55]
Weight of steel (thickness 0.7mm)[b] [kg/m^2]	6.8 [55]
External Wall, Windows and Doors	
Built up aluminium wall cladding with 130 thick insulation [a] [m^2]	2695[c]
Weight of aluminium cladding (thickness 0.9mm)[b] [kg/m^2]	4.0 [55]
Weight of steel (thickness 0.7mm)[c] [kg/m^2]	6.8 [55]
Curtain wall[a], b [m^2]	525
Glass[b] [kg/m^2]	10mm double glass, 50 kg/m^2
Curtain wall - steel frame [kg/m^2]	19 kg/m^2
Curtain wall - aluminium frame [kg/m^2]	19 kg/m^2
2.5 m high inner leaf of 140 thick fairface blockwork [a] [m^2]	350
Bricks [per m^2]	215 x 102.5 x 65 mm 60 bricks per m^2
Cement mortar [kg/m^2 of the wall]	0.02 m^3/m^2, sand:cement ratio - 3:1, density 2080 kg/m^3
3000 x 4600 mm high steel sectional overhead doors[a] [item]	12
Steel weight per m^2	0.9kg/^{2} [56]
Aluminium weight per m^2	0.45kg/^{2} [56]
Aluminium single entrance doors[a], no glass [item]	8
Size[b] [m]	1.0x2.0
Weight per m^2	21 kg/m^2
Coated aluminum double glazed window system[a] [m^2]	50
Aluminium sections[b] [kg/m^2]	14 kg/m^2 of door [43]
Partitions and Doors	
2 hour fire resistant blockwork party walls [m^2]	300
Block per m^2 of wall[a]	10 blocks/m^2 (440x215x100mm)
Cement mortar per m^2 of wall[a]	0.02 m^3/m^2
Metal stud partitions[a] [m^2]	100
Weight of studs [kg/m^2 of the wall]	5.3 [32]
Laminated faced internal doorset with softwood frames [item]	10
Size[a] [m]	0.9x2.0
Wall finishes (internal walls)	
Cement plaster, sand:cement ratio - 4:1, density 2040 kg/m^3 [m^3/m^2]	0.01

[a] Assumptions
[b] Assumed the share of aluminum / steel cladding as 50% / 50%
[c] Assumed 10% allowance for ground beams

4.3 Retail buildings (RB)

The VOA [44] divide Retail buildings into Financial & Professional Services (FPS) and Shops (S). Due to the large variety of possible sizes of buildings, for this study a mix of office and industrial buildings were assumed according to Table 19. The shares of building typologies were consulted with and agreed with industry partners.

Material assumptions for office buildings and industrial units used for the Retail buildings are included above, in Sections 4.1 and 4.2.

Table 19: Retail buildings - assumptions

Sub-sector	Typology	Equivalent to	Share within category	Share within sub-sector
Financial and Professional Services (FPS)	Low Rise office building (OLR)	Financial and Professional Services (FPS)	100%	35%
Shops (S)	Low Rise office building (OLR)	Shopping centre	20%	65%
	Small size industrial unit (SIU)	Supermarket	40%	
	Medium size industrial unit (MIU)	Superstore	10%	
	Large size industrial unit (LIU)	Distribution centre	30%	

4.4 Other buildings (OB)

The Valuation Office Agency (ONS) [44] divide Other sector in 12 subsections. Due to wide variety of buildings included in "Other" sector, material intensity per m^2 was assumed as an average from all materials (elements) calculated for domestic, Office, Retail and Industrial buildings (excluding conversions).

4.5 Infrastructure and other

Although non-building construction accounts for a significant proportion of UK construction material use, the diversity of projects and structures this includes makes the use of a bottom-up approach based on standard typologies problematic. Infrastructure and other construction are still included in this study for completeness, however, using available statistics.

For this sector, material intensity was calculated for concrete (ready mix-concrete, cement), steel reiforcement and constructional steelworks. Ready Mixed Concrete Organization (ERMCO) [3] reported that 25% out of 22.5 Mm^3 (54 Mt) of ready mix concrete (RMC) in the UK in 2018 was used in infrastructure, 5% for pavements, 5% concrete roads and 10% other use (RMC). The volume of steel reinforcement for these uses is unknown so the steel reinforcement intensity assumed (Table 20). Other use of cement such as for external works, refurbishment, repairs, extensions and maintenance are not included in ERMCO statistics. For this reason the 'Other use' of cement reported by MPA [57] was taken for this study (0.5 Mt). Other use of RMC was taken from RMC 'Other use' included in ERMCO statistics (5.4 Mt)[3]. Other use of precast concrete was calculated as the difference between total concrete reported and the volume of RMC reported by ERMCO (37 Mt - 22.5 Mt = 14.5 Mt). All calculated precast elements used in new domestic and non-domestic buildings (including concrete blocks, tiles, concrete facade and precast floor systems) have been subtracted from this (14.5 Mt - 2.9 Mt = 12.3 Mt). According to the information obtained from the Industry partners, the share between 'Infrastructure' and 'Other use' was assumed as 30/70.

The British Construction Steel Association (BCSA [2]) reported the consumption of constructional steelworks (rolled sections, fabricated sections, hollow sections, light sections) in infrastructure as 160 kt and other (incl. agriculture) 27kt. These volumes were taken for the analysis.

Table 20 presents general assumptions used to calculate cement, steel reinforcement and constructional steelworks for infrastructure, pavements, concrete roads and 'Other use'.

Table 20: General assumption for material use in infrastructure, pavements, concrete roads and other use - 2018

	RMC [3]	Precast	Cement	Reiforcement	Reiforcement	Constructional steelworks [2]
	kt	kt	kt	kg/m^3	kt	kt
	Infrastructure, pavements, concrete roads					
Infrastructure RMC[a]	13,500	-	1,563	80[e]	375	-
Infrastructure PC[b]	-	3,700	650	80[e]	-	-
Infrastructure Ssec[c]	-	-	-	-	-	160
Pavements RMC[a]	2,700	-	313	-	-	-
Concrete roads RMC[a]	2,700	-	313	-	-	-
	Other use[d]					
Other use RMC[a]	5,400	-	625	-	-	-
Other use cement	-	-	500	-	-	-
Other use PC[b]	-	8,600	1,00	70[e]	-	-
Other use Ssec[c]	-	-	-	-	-	27

[a] RMC - Ready-mix concrete
[b] PC - precast concrete, the share of PC used in Infrastructure and Other use as 30/70.
[c] Ssec - Steel sections
[d] Other use include external works, refurbishment, repairs, extensions and maintenance
[e] assumed that 1/2 of concrete is reinforced

5 Assessment of demolitions

The UK generated 222.2 Mt of waste in 2018, with England responsible for 84% of this [58]. Construction and demolition waste (C&D) represented 30% of the UK waste (67.8 Mt) with a recovery rate 92.3%. The National Federation of Demolition Contractors (NFDC) reported that 98.8% of non-hazardous waste from demolition was sent to recycling or reuse and therefore the recovery rate is higher than C&D recovery rate. NFDC representing 80% of UK demolition works reported 20 Mt hardcore waste from demolition in 2018 [59]. Scaling this to cover the UK, and using a NFDC recovery rate (98.8%) it gives 25.31 Mt hardcore from demolition. From the information received from the NFDC, the shares of hardcore demolition waste between infrastructure and buildings are approximately 40% and 60% respectively. Since 2006, demolition of dwellings decreased from 25,064 to 9,477 in 2018, and is the lowest reported in this period [8]. The Valuation Office Agency (ONS) [44] presents only a change in number and floor area of non-domestic properties stock (net change). There is no information on the number of new non-domestic buildings completions. For the purpose of this study, the number (floor area) of demolitions of non-domestic buildings by typologies were calculated using calculated material intensity that could be considered as a hardcore waste in the end of their lives. They include concrete, concrete blocks, bricks, tiles, stone blocks, etc. The share and volume of hardcore waste presents Table 21 and calculated floor area of demolitions in 2018 - Table 22.

Table 21: Calculations of demolition rate for domestic and non-domestic buildings

	Share	Hardcore [kt]
Infrastructure / roads	40.0%	10,126
Buildings	60.0%	**15,189**
SUM	100.0%	25,315

	Floor area of demolitions	Hardcore [kt]
Domestic [8]	864,500 [8]	1,047

av. hardcore 1.21 kg/m^2 (calculated) x 9,500 dwellings x 91m^2 (av. floor area)

	Share (calculations)	Hardcore [kt]
Domestic [8]	6.9 %	1,047
Non-domestic (calculated)	93.1%	**14,142**
SUM	100%	15,189

	Share by floor area in non-domestic building stock [44]	Hardcore [kt]
Office buildings	16.8%	2,376
Industrial buildings	54.9%	7,764
Retail buildings	17.7%	2,503
Other buildings	10.6%	1,499
SUM	100%	**14,142**

Table 22: Floor area of demolitions in 2018

	hardcore per m^2	Floor area of demolitions in 2018 [thousand m^2]
Domestic	1.21	864
Office buildings	1.53[a]	1,553
Industrial buildings	0.90[a]	8,627
Retail buildings	0.97[a]	2,580
Other buildings	1.42[a]	1,056
SUM	-	14,680

[a] calculated value has been increased by 5% as assumed that more materials were used when these buildings were built.

6 Material allowances due to structural inefficiency and grid irregularity

Table 23: Material allowances due to structural inefficiency and grid irregularity

Element	E-T,M-T S-D,D B,C-F LRF<4 4≤LRF≤6 7≤LRF≤10 HRF>10	O (OLR) (OHR)	IB (SIU) (MIU) (LIU)	RB
Foundations - strip concrete	1.2	1.3	1.3	1.3
Foundations - strip reinforcement	1.1	1.1	1.1	1.1
Foundations - piles, caps, beams - concrete	1.2	1.3	1.3	1.3
Foundations - piles, caps, beams reinforcement	1.1	1.1	1.1	1.1
Foundations - pile raft foundation - concrete	1.2	1.3	1.3	1.3
Foundations - pile raft foundation - reinforcement	1.1	1.1	1.1	1.1
Foundations - pad foundation - concrete	1.2	1.3	1.3	1.3
Foundations - pad foundation - reinforcement	1.1	1.1	1.1	1.1
Foundation - retaining walls - concrete	1.2	1.3	1.3	1.3
Foundation - retaining walls - reinforcement	1.1	1.1	1.1	1.1
Ground floor - concrete	1.2	1.3	1.3	1.3
Ground floor - reinforcement	1.1	1.1	1.1	1.1
Ground floor - prefab beams	1.2	1.3	1.3	1.3
Ground floor - prefab beams reinforcement	1.1	1.1	1.1	1.1
Ground floor - dense blocks	1.2	1.3	1.3	1.3
Ground floor - screed	1.2	1.3	1.3	1.3
Load bearing walls (cavity) - concrete blocks	1.1	1.1	1.1	1.1
Load bearing walls (cavity) - concrete blocks - mortar	1.1	1.1	1.1	1.1
Load bearing walls (cavity) - concrete blocks - cement plaster	1.1	1.1	1.1	1.1
Load bearing walls (cavity) - concrete blocks - gypsum plaster	1.1	1.1	1.1	1.1
Load bearing walls (cavity) - clay blocks	1.1	1.1	1.1	1.1
Load bearing walls (cavity) - clay blocks - mortar	1.1	1.1	1.1	1.1
Load bearing walls (cavity) - clay blocks - cement plaster	1.1	1.1	1.1	1.1
Load bearing walls (cavity) - clay blocks - gypsum plaster	1.1	1.1	1.1	1.1
Load bearing walls (one layer) - clay blocks	1.1	1.1	1.1	1.1
Load bearing walls (one layer) - clay blocks - mortar	1.1	1.1	1.1	1.1
Load bearing walls (one layer) - clay blocks - cement plaster	1.1	1.1	1.1	1.1
Load bearing walls (one layer) - clay blocks - gypsum plaster	1.1	1.1	1.1	1.1
Load bearing walls - METSEC cold rolled sections	1.1	1.1	1.0	1.0
Load bearing walls - METSEC - plasterboard	1.0	1.0	1.0	1.0
Load bearing walls - METSEC gypsum plaster	1.1	1.1	1.1	1.1
Load bearing walls - concrete walls - concrete	1.2	1.1	1.1	1.1
Load bearing walls - concrete walls - reiforcement	1.1	1.1	1.1	1.1
Load bearing walls - concrete walls - cement plaster	1.1	1.1	1.1	1.1
Load bearing walls - concrete walls - gypsum plaster	1.1	1.1	1.1	1.1
Steel frame - cold rolled sections	1.2	1.2	1.2	1.2
Steel frame - plasterboard	1.0	1.0	1.0	1.0
Steel frame - gypsum plaster	1.1	1.1	1.1	1.1
Concrete frame - cold rolled sections	1.1	1.1	1.1	1.1
Concrete frame - plasterboard	1.0	1.0	1.0	1.0
Concrete frame - gypsum plaster	1.1	1.1	1.1	1.1

Timber frame - plasterboard	1.0	1.0	1.0	1.0
Timber frame - gypsum plaster	1.1	1.1	1.1	1.1
Solid wall - bricks	1.1	1.1	1.1	1.1
Solid wall - bricks, mortar	1.1	1.1	1.1	1.1
Solid wall - bricks, cememt plaster	1.1	1.1	1.1	1.1
Solid wall - stone	1.1	1.1	1.1	1.1
Solid wall - stone, mortar	1.1	1.1	1.1	1.1
Solid wall - stone, cement plaster	1.1	1.1	1.1	1.1
Partitions - concrete blocks	1.1	1.1	1.1	1.1
Partitions - concrete blocks - mortar	1.1	1.1	1.1	1.1
Partitions - concrete blocks - cement plaster	1.1	1.1	1.1	1.1
Partitions - concrete blocks - gypsum plaster	1.1	1.1	1.1	1.1
Partitions - bricks	1.1	1.1	1.1	1.1
Partitions - bricks - mortar	1.1	1.1	1.1	1.1
Partitions - bricks - cement plaster	1.1	1.1	1.1	1.1
Partitions - timber - frame	1.1	1.2	1.2	1.2
Partitions - timber - plasterboard	1.0	1.0	1.0	1.0
Partitions - timber - gypsum plaster	1.1	1.1	1.1	1.1
Partitions - METSEC cold rolled sections	1.1	1.1	1.1	1.1
Partitions - METSEC plasterboard	1.0	1.0	1.0	1.0
Partitions - METSEC gypsum plaster	1.1	1.1	1.1	1.1
Partitions - concrete walls - concrete	1.2	1.1	1.1	1.1
Partitions - concrete walls - rebars	1.1	1.1	1.1	1.1
Partitions - concrete walls - cement plaster	1.1	1.1	1.1	1.1
Partitions - concrete walls - gypsum plaster	1.1	1.1	1.1	1.1
Partitions - clay blocks	1.1	1.1	1.1	1.1
Partitions - clay blocks - mortar	1.1	1.1	1.1	1.1
Partitions - clay blocks - cement plaster	1.1	1.1	1.1	1.1
Partitions - clay blocks - gypsum plaster	1.1	1.1	1.1	1.1
Frame - steel hot rolled	1.3	1.3	1.2	1.3
Frame - fabricated (fabsec)	1.1	1.3	1.2	1.3
Frame - RC	1.2	1.3	1.2	1.3
Frame - RC - reinforcement	1.1	1.1	1.1	1.1
Frame - timber frame	1.1	1.3	1.2	1.2
Lift shaft - concrete	1.2	1.2	1.2	1.2
Lift shaft - reinforcement	1.1	1.1	1.1	1.1
Stairs - concrete	1.2	1.3	1.3	1.3
Stairs - reinforcement	1.1	1.1	1.1	1.1
Cavity walls (no render) - cold rolled sections	1.1	1.1	1.1	1.1
Cavity walls (no render) - bricks	1.1	1.1	1.1	1.1
Cavity walls (no render) - bricks - mortar	1.1	1.1	1.1	1.1
Cavity walls (render) - bricks	1.1	1.1	1.1	1.1
Cavity walls (render) - bricks - mortar	1.1	1.1	1.1	1.1
Cavity walls (render) - bricks - render	1.1	1.1	1.1	1.1
Cavity walls (no render) - stone	1.1	1.1	1.1	1.1
Cavity walls (no render) - stone - mortar	1.1	1.1	1.1	1.1
One leaf wall - render	1.1	1.1	1.1	1.1
Brick slips - slips	1.1	1.1	1.1	1.1
Brick slips - mortar	1.1	1.1	1.1	1.1
Metal cladding - cold rolled sections	1.1	1.1	1.1	1.1
Metal cladding - steel pannels	1.1	1.1	1.1	1.1
Metal cladding - aluminium pannels	1.1	1.1	1.1	1.1
Conrete cladding - cold rolled sections	1.1	1.1	1.1	1.1
Conrete cladding - pannels	1.1	1.1	1.1	1.1

Timber cladding	1.1	1.1	1.1	1.1
Curtain wall - steel	1.1	1.1	1.1	1.1
Curtain wall - aluminium	1.1	1.1	1.1	1.1
Curtain wall - glass	1.0	1.0	1.0	1.0
Concrete frame - Render	1.1	1.1	1.1	1.1
Floor - Timber - beams and floor	1.2	1.2	1.2	1.2
Floor - Timber - plasterboard	1.1	1.1	1.1	1.1
Floor - Timber - gypsum plaster	1.1	1.1	1.1	1.1
Floor - Hollowcore concrete	1.2	1.3	1.3	1.3
Floor - Hollowcore reinforcement	1.1	1.1	1.1	1.1
Floor - Hollowcore topping concrete	1.2	1.2	1.3	1.3
Floor - Hollowcore topping reinforcement	1.1	1.1	1.1	1.1
Floor - Hollowcore cement plaster	1.1	1.1	1.1	1.1
Floor - Hollowcore gypsum plaster	1.1	1.1	1.1	1.1
Floor - flat slab - concrete	1.2	1.3	1.3	1.3
Floor - flat slab reinforcement	1.1	1.1	1.1	1.1
Floor - flat slab - cement plaster	1.1	1.1	1.1	1.1
Floor - flat slab - gypsum plaster	1.1	1.1	1.1	1.1
Floor - composite floor - steel sections	1.2	1.3	1.3	1.3
Floor - composite floor - steel deck	1.2	1.2	1.2	1.2
Floor - composite floor - concrete	1.2	1.3	1.3	1.3
Floor - composite floor - reinforcement	1.1	1.1	1.1	1.1
Floor - composite floor - plasterboard	1.1	1.1	1.1	1.1
Floor - composite floor - gypsum plaster	1.1	1.1	1.1	1.1
Floor - PT slab - concrete	1.2	1.3	1.3	1.3
Floor - PT slab - reinforcement	1.1	1.1	1.1	1.1
Roof - timber structure	1.2	1.2	1.2	1.2
Roof - timber structure - plasterboard	1.1	1.1	1.1	1.1
Roof - timber structure - gypsum plaster	1.1	1.1	1.1	1.1
Roof - hollowcore - concrete	1.2	1.3	1.3	1.3
Roof - hollowcore reinforcement	1.1	1.1	1.1	1.1
Roof - hollowcore - topping - concrete	1.2	1.2	1.2	1.2
Roof - hollowcore - topping - reinforcement	1.1	1.1	1.1	1.1
Roof - hollowcore cement plaster	1.0	1.0	1.0	1.0
Roof - hollowcore gypsum plaster	1.0	1.0	1.0	1.0
Roof - flat slab - concrete	1.2	1.3	1.3	1.3
Roof - flat slab - reinforcement	1.1	1.1	1.1	1.1
Roof - flat slab - cement plaster	1.0	1.0	1.0	1.0
Roof - flat slab - gypsum plaster	1.0	1.0	1.0	1.0
Roof - PT - concrete	1.2	1.3	1.3	1.3
Roof - PT - reinforcement	1.1	1.1	1.1	1.1
Roof - METSEC - sections	1.2	1.2	1.2	1.2
Roof - METSEC - panells	1.0	1.0	1.0	1.0
Roof - aluminium pannels	1.0	1.0	1.0	1.0
Roof - steel pannels	1.0	1.0	1.0	1.0
Roof - composite - concrete	1.2	1.3	1.3	1.3
Roof - composite - reinforcement	1.1	1.1	1.1	1.1
Roof - composite - steel deck	1.2	1.2	1.2	1.2
Roof - composite - plasterboard	1.0	1.0	1.0	1.0
Roof - composite - gypsum plaster	1.0	1.0	1.0	1.0
Roof Tiles - Plain interlocking concrete tiles	1.0	1.0	1.0	1.0
Roof Tiles - Plain clay tiles	1.0	1.0	1.0	1.0
Roof Tiles - Natural Welsh slates	1.0	1.0	1.0	1.0
Internal doors - steel frame, laminated leaf - leaf	1.0	1.0	1.0	1.0

Internal doors - steel frame, laminated leaf - steel frame	1.0	1.0	1.0	1.0
Internal doors - timber frame, timber leaf	1.0	1.0	1.0	1.0
Internal doors - glass	1.0	1.0	1.0	1.0
External doors - PVC	1.0	1.0	1.0	1.0
External doors - timber frame, timber leaf	1.0	1.0	1.0	1.0
External doors - steel frame, steel leaf	1.0	1.0	1.0	1.0
External doors - glass	1.0	1.0	1.0	1.0
External doors - steel frame, laminated leaf - frame	1.0	1.0	1.0	1.0
External doors - steel frame, laminated leaf - leaf	1.0	1.0	1.0	1.0
Windows - PVC frame	1.0	1.0	1.0	1.0
Windows - PVC, glass	1.0	1.0	1.0	1.0
Windows - timber frame	1.0	1.0	1.0	1.0
Windows - timber, glass	1.0	1.0	1.0	1.0
Windows - aluminium frame	1.0	1.0	1.0	1.0
Windows - aluminium, glass	1.0	1.0	1.0	1.0

7 Material quantities for each typology per gross internal floor area

Table 24: Material quantities for each typology per gross internal floor area - E-T, M-T, S-D, D, B, C-F

Element	E-T	M-T	S-D	D	B	C-F
Foundations - strip concrete	314.6	281.2	403.1	380.3	542.0	-
Foundations - strip reinforcement	3.8	3.3	4.7	4.5	6.5	-
Foundations - piles, caps, beams - concrete	11.7	11.3	15.0	14.2	20.2	-
Foundations - piles, caps, beams reinforcement	0.4	0.4	0.5	0.5	0.7	-
Foundations - pile raft foundation - concrete	-	-	-	-	-	-
Foundations - pile raft foundation - reinforcement	-	-	-	-	-	-
Foundations - pad foundation - concrete	1.0	0.7	0.8	0.4	1.4	-
Foundations - pad foundation - reinforcement	0.0	0.0	0.0	0.0	0.1	-
Foundation - retaining walls - concrete	130.2	68.4	120.8	182.0	270.3	-
Foundation - retaining walls - reinforcement	3.3	1.7	3.1	4.6	6.9	-
Ground floor - concrete	82.8	82.8	82.8	82.8	165.6	34.8
Ground floor - reinforcement	8.2	8.2	8.2	8.2	16.4	3.4
Ground floor - prefab beams	15.7	15.7	15.7	15.7	31.5	6.6
Ground floor - prefab beams reinforcement	0.8	0.8	0.8	0.8	1.7	0.4
Ground floor - dense blocks	41.6	41.6	41.6	41.6	83.2	17.5
Ground floor - screed	49.7	49.7	49.7	49.7	99.4	20.9
Load bearing walls (cavity) - concrete blocks	153.0	112.6	145.5	178.9	137.2	78.1
Load bearing walls (cavity) - concrete blocks - mortar	25.1	18.5	23.8	29.3	22.5	13.4
Load bearing walls (cavity) - concrete blocks - cement plaster	31.4	31.4	26.2	18.8	32.7	56.1
Load bearing walls (cavity) - concrete blocks - gypsum plaster	2.3	2.3	1.7	2.1	1.4	4.0
Load bearing walls (cavity) - clay blocks	-	-	-	-	-	-
Load bearing walls (cavity) - clay blocks - mortar	-	-	-	-	-	-
Load bearing walls (cavity) - clay blocks - cement plaster	-	-	-	-	-	-
Load bearing walls (cavity) - clay blocks - gypsum plaster	-	-	-	-	-	-
Load bearing walls (one layer) - clay blocks	-	-	-	-	-	-
Load bearing walls (one layer) - clay blocks - mortar	-	-	-	-	-	-
Load bearing walls (one layer) - clay blocks - cement plaster	-	-	-	-	-	-
Load bearing walls (one layer) - clay blocks - gypsum plaster	-	-	-	-	-	-
Load bearing walls - METSEC cold rolled sections	-	-	-	-	-	-
Load bearing walls - METSEC - plasterboard	-	-	-	-	-	-
Load bearing walls - METSEC gypsum plaster	-	-	-	-	-	-

Load bearing walls - concrete walls - concrete	-	-	-	-	-	-
Load bearing walls - concrete walls - reinforcement	-	-	-	-	-	-
Load bearing walls - concrete walls - cement plaster	-	-	-	-	-	-
Load bearing walls - concrete walls - gypsum plaster	-	-	-	-	-	-
Steel frame - cold rolled sections	0.1	0.1	0.1	0.2	0.1	0.1
Steel frame - plasterboard	0.2	0.2	0.2	0.2	0.2	0.4
Steel frame - gypsum plaster	0.0	0.0	0.0	0.0	0.0	0.1
Concrete frame - cold rolled sections	-	-	-	-	-	-
Concrete frame - plasterboard	-	-	-	-	-	-
Concrete frame - gypsum plaster	-	-	-	-	-	-
Timber frame - plasterboard	2.4	2.4	1.8	2.2	1.4	4.0
Timber frame - gypsum plaster	0.5	0.5	0.4	0.5	0.3	1.0
Solid wall - bricks	-	-	-	-	-	-
Solid wall - bricks, mortar	-	-	-	-	-	-
Solid wall - bricks, cememt plaster	-	-	-	-	-	-
Solid wall - stone	-	-	-	-	-	-
Solid wall - stone, mortar	-	-	-	-	-	-
Solid wall - stone, cement plaster	-	-	-	-	-	-
Partitions - concrete blocks	110.1	110.1	96.4	71.7	101.4	123.5
Partitions - concrete blocks - mortar	13.3	13.3	11.7	8.7	12.3	14.9
Partitions - concrete blocks - cement plaster	31.4	31.4	26.2	18.8	32.7	35.2
Partitions - concrete blocks - gypsum plaster	2.4	2.4	2.1	1.5	2.2	2.6
Partitions - bricks	-	-	-	-	-	-
Partitions - bricks - mortar	-	-	-	-	-	-
Partitions - bricks - cement plaster	-	-	-	-	-	-
Partitions - timber - frame	4.2	4.2	3.7	2.7	3.9	4.7
Partitions - timber - plasterboard	6.7	6.7	5.8	4.3	6.1	7.5
Partitions - timber - gypsum plaster	1.6	1.6	1.4	1.0	1.4	1.8
Partitions - METSEC cold rolled sections	-	-	-	-	-	-
Partitions - METSEC plasterboard	-	-	-	-	-	-
Partitions - METSEC gypsum plaster	-	-	-	-	-	-
Partitions - concrete walls - concrete	-	-	-	-	-	-
Partitions - concrete walls - rebars	-	-	-	-	-	-
Partitions - concrete walls - cement plaster	-	-	-	-	-	-
Partitions - concrete walls - gypsum plaster	-	-	-	-	-	-
Partitions - clay blocks	-	-	-	-	-	-
Partitions - clay blocks - mortar	-	-	-	-	-	-
Partitions - clay blocks - cement plaster	-	-	-	-	-	-
Partitions - clay blocks - gypsum plaster	-	-	-	-	-	-
Frame - steel hot rolled	0.4	0.4	0.4	0.4	0.4	0.3
Frame - fabricated (fabsec)	-	-	-	-	-	-
Frame - RC	-	-	-	-	-	-
Frame - RC - reinforcement	-	-	-	-	-	-
Frame - timber frame	4.0	2.9	3.8	4.7	3.6	2.1
Lift shaft - concrete	-	-	-	-	-	-
Lift shaft - reinforcement	-	-	-	-	-	-
Stairs - concrete	-	-	-	-	-	-
Stairs - reinforcement	-	-	-	-	-	-
Cavity walls (no render) - cold rolled sections	-	-	-	-	-	-
Cavity walls (no render) - bricks	170.9	64.8	165.4	234.5	179.8	105.2
Cavity walls (no render) - bricks - mortar	42.7	16.2	47.7	58.6	45.0	27.6
Cavity walls (render) - bricks	10.7	4.1	10.3	14.7	11.2	6.6
Cavity walls (render) - bricks - mortar	2.7	1.0	3.0	3.7	2.8	1.7
Cavity walls (render) - bricks - render	2.3	0.9	1.8	1.9	2.5	2.5

Cavity walls (no render) - stone	10.4	4.0	10.1	14.3	11.0	6.4
Cavity walls (no render) - stone - mortar	2.7	1.0	3.0	3.7	2.8	1.7
One leaf wall - render	1.1	0.4	0.9	0.9	1.3	1.3
Brick slips - slips	0.5	0.2	0.8	0.7	0.5	0.3
Brick slips - mortar	1.0	0.4	1.0	1.4	0.9	0.6
Metal cladding - steel pannels	-	-	-	-	-	-
Metal cladding - aluminium pannels	-	-	-	-	-	-
Conrete cladding - cold rolled sections	-	-	-	-	-	-
Conrete cladding - pannels	-	-	-	-	-	-
Timber cladding	0.7	0.3	1.0	0.7	0.7	0.4
Curtain wall - steel	-	-	-	-	-	-
Curtain wall - aluminium	-	-	-	-	-	-
Curtain wall - glass	-	-	-	-	-	-
Concrete frame - Render	-	-	-	-	-	-
Floor - Timber - beams and floor	7.3	7.3	7.3	7.3	-	-
Floor - Timber - plasterboard	2.8	2.8	2.8	2.8	-	-
Floor - Timber - gypsum plaster	0.6	0.6	0.6	0.6	-	-
Floor - Hollowcore concrete	55.2	55.2	55.2	55.2	-	-
Floor - Hollowcore reinforcement	0.6	0.6	0.6	0.6	-	-
Floor - Hollowcore topping concrete	55.2	55.2	55.2	55.2	-	-
Floor - Hollowcore topping reinforcement	0.9	0.9	0.9	0.9	-	-
Floor - Hollowcore cement plaster	5.4	5.4	4.5	3.2	-	-
Floor - Hollowcore gypsum plaster	0.4	0.4	0.4	0.4	-	-
Floor - flat slab - concrete	-	-	-	-	-	-
Floor - flat slab reinforcement	-	-	-	-	-	-
Floor - flat slab - cement plaster	-	-	-	-	-	-
Floor - flat slab - gypsum plaster	-	-	-	-	-	-
Floor - composite floor - steel sections	-	-	-	-	-	-
Floor - composite floor - steel deck	-	-	-	-	-	-
Floor - composite floor - concrete	-	-	-	-	-	-
Floor - composite floor - reinforcement	-	-	-	-	-	-
Floor - composite floor - plasterboard	-	-	-	-	-	-
Floor - composite floor - gypsum plaster	-	-	-	-	-	-
Floor - PT slab - concrete	-	-	-	-	-	-
Floor - PT slab - reinforcement	-	-	-	-	-	-
Roof - timber structure	9.5	9.5	9.5	9.5	19.1	1.3
Roof - timber structure - plasterboard	1.7	1.7	1.7	1.7	3.4	0.4
Roof - timber structure - gypsum plaster	0.4	0.4	0.4	0.4	0.7	0.1
Roof - hollowcore - concrete	22.1	22.1	22.1	22.1	44.2	11.0
Roof - hollowcore reinforcement	0.3	0.3	0.3	0.3	0.5	0.3
Roof - hollowcore - topping - concrete	22.1	22.1	22.1	22.1	44.2	23.2
Roof - hollowcore - topping - reinforcement	0.4	0.4	0.4	0.4	0.7	0.4
Roof - hollowcore cement plaster	2.0	2.0	1.6	1.2	2.4	2.1
Roof - hollowcore gypsum plaster	0.1	0.1	0.1	0.1	0.3	0.2
Roof - flat slab - concrete	-	-	-	-	-	46.4
Roof - flat slab - reinforcement	-	-	-	-	-	1.1
Roof - flat slab - cement plaster	-	-	-	-	-	2.1
Roof - flat slab - gypsum plaster	-	-	-	-	-	0.2
Roof - PT - concrete	-	-	-	-	-	-
Roof - PT - reinforcement	-	-	-	-	-	-
Roof - METSEC - sections	-	-	-	-	-	-
Roof - METSEC - panells	-	-	-	-	-	-
Roof - aluminium pannels	-	-	-	-	-	-
Roof - steel pannels	-	-	-	-	-	-

Roof - composite - concrete	-	-	-	-	-	-
Roof - composite - reinforcement	-	-	-	-	-	-
Roof - composite - steel deck	-	-	-	-	-	-
Roof - composite - plasterboard	-	-	-	-	-	-
Roof - composite - gypsum plaster	-	-	-	-	-	-
Roof Tiles - Plain interlocking concrete tiles	11.3	11.3	12.3	12.5	27.0	0.8
Roof Tiles - Plain clay tiles	15.1	15.1	16.3	16.6	36.0	1.1
Roof Tiles - Natural Welsh slates	7.5	7.5	8.2	8.3	18.0	0.6
Internal doors - steel frame, laminated leaf - leaf	1.1	1.1	0.9	1.0	0.8	1.0
Internal doors - steel frame, laminated leaf - steel frame	0.7	0.7	0.6	0.6	0.5	0.6
Internal doors - timber frame, timber leaf	0.8	0.8	0.7	0.8	0.6	0.8
Internal doors - glass	0.0	0.0	0.0	0.0	0.0	0.0
External doors - PVC	0.3	0.3	0.2	0.5	0.7	0.4
External doors - timber frame, timber leaf	0.2	0.2	0.2	0.3	0.5	0.3
External doors - steel frame, steel leaf	0.2	0.2	0.2	0.3	0.4	0.2
External doors - glass	0.1	0.1	0.1	0.1	0.2	0.1
External doors - steel frame, laminated leaf - frame	0.1	0.1	0.1	0.2	0.3	0.1
External doors - steel frame, laminated leaf - leaf	0.1	0.1	0.1	0.1	0.2	0.1
Windows - PVC frame	1.3	1.3	1.0	0.9	1.2	0.8
Windows - PVC, glass	2.8	2.8	2.3	1.9	2.7	1.9
Windows - timber frame	0.4	0.4	0.3	0.2	0.3	0.2
Windows - timber, glass	0.3	0.3	0.3	0.2	0.3	0.2
Windows - aluminium frame	-	-	-	-	-	-
Windows - aluminium, glass	-	-	-	-	-	-

Table 25: Material quantities for each typology per gross internal floor area - LRF<4, 4≤LRF≤6, 7≤HRF≤10, HRF>10

Element	LRF<4,	4≤LRF≤6	7≤HRF≤10	HRF>10
Foundations - strip concrete	-	-	-	-
Foundations - strip reinforcement	-	-	-	-
Foundations - piles, caps, beams - concrete	52.2	22.2	10.4	20.8
Foundations - piles, caps, beams reinforcement	1.8	0.8	0.4	0.7
Foundations - pile raft foundation - concrete	-	-	66.3	4.0
Foundations - pile raft foundation - reinforcement	-	-	2.3	0.1
Foundations - pad foundation - concrete	53.1	28.5	10.6	-
Foundations - pad foundation - reinforcement	2.2	1.2	0.4	-
Foundation - retaining walls - concrete	75.4	50.3	30.2	20.1
Foundation - retaining walls - reinforcement	2.7	1.8	1.1	0.7
Ground floor - concrete	69.6	13.0	34.8	5.8
Ground floor - reinforcement	6.9	1.3	3.4	4.0
Ground floor - prefab beams	2.2	0.2	-	-
Ground floor - prefab beams reinforcement	0.1	0.0	-	-
Ground floor - dense blocks	5.8	0.5	-	-
Ground floor - screed	7.0	0.6	-	-
Load bearing walls (cavity) - concrete blocks	156.1	-	-	-
Load bearing walls (cavity) - concrete blocks - mortar	26.9	-	-	-
Load bearing walls (cavity) - concrete blocks - cement plaster	56.1	-	-	-
Load bearing walls (cavity) - concrete blocks - gypsum plaster	4.0	-	-	-
Load bearing walls (cavity) - clay blocks	-	-	-	-
Load bearing walls (cavity) - clay blocks - mortar	-	-	-	-
Load bearing walls (cavity) - clay blocks - cement plaster	-	-	-	-
Load bearing walls (cavity) - clay blocks - gypsum plaster	-	-	-	-
Load bearing walls (one layer) - clay blocks	-	-	-	-

Load bearing walls (one layer) - clay blocks - mortar	-	-	-	-
Load bearing walls (one layer) - clay blocks - cement plaster	-	-	-	-
Load bearing walls (one layer) - clay blocks - gypsum plaster	-	-	-	-
Load bearing walls - METSEC cold rolled sections	-	6.2	6.2	6.2
Load bearing walls - METSEC - plasterboard	-	34.0	34.0	34.0
Load bearing walls - METSEC gypsum plaster	-	2.0	2.0	2.0
Load bearing walls - concrete walls - concrete	75.4	119.1	39.7	39.7
Load bearing walls - concrete walls - reinforcement	2.3	3.6	1.2	1.2
Load bearing walls - concrete walls - cement plaster	13.3	21.0	7.0	7.0
Load bearing walls - concrete walls - gypsum plaster	1.0	1.6	0.5	0.5
Steel frame - cold rolled sections	0.1	0.8	0.8	0.8
Steel frame - plasterboard	0.4	8.5	8.5	8.5
Steel frame - gypsum plaster	0.1	0.5	0.5	0.5
Concrete frame - cold rolled sections	-	1.6	3.2	3.2
Concrete frame - plasterboard	-	17.0	34.0	34.0
Concrete frame - gypsum plaster	-	1.0	2.0	2.0
Timber frame - plasterboard	-	-	-	-
Timber frame - gypsum plaster	-	-	-	-
Solid wall - bricks	-	-	-	-
Solid wall - bricks, mortar	-	-	-	-
Solid wall - bricks, cememt plaster	-	-	-	-
Solid wall - stone	-	-	-	-
Solid wall - stone, mortar	-	-	-	-
Solid wall - stone, cement plaster	-	-	-	-
Partitions - concrete blocks	144.1	102.9	-	-
Partitions - concrete blocks - mortar	17.4	12.5	-	-
Partitions - concrete blocks - cement plaster	41.0	29.3	-	-
Partitions - concrete blocks - gypsum plaster	3.1	2.2	-	-
Partitions - bricks	-	-	-	-
Partitions - bricks - mortar	-	-	-	-
Partitions - bricks - cement plaster	-	-	-	-
Partitions - timber - frame	3.5	2.4	-	-
Partitions - timber - plasterboard	5.6	3.7	-	-
Partitions - timber - gypsum plaster	1.3	0.9	-	-
Partitions - METSEC cold rolled sections	-	1.6	6.4	6.4
Partitions - METSEC plasterboard	-	9.3	37.3	37.3
Partitions - METSEC gypsum plaster	-	14.0	56.0	56.0
Partitions - concrete walls - concrete	-	15.0	-	-
Partitions - concrete walls - rebars	-	0.4	-	-
Partitions - concrete walls - cement plaster	-	2.9	-	-
Partitions - concrete walls - gypsum plaster	-	0.2	-	-
Partitions - clay blocks	-	-	-	-
Partitions - clay blocks - mortar	-	-	-	-
Partitions - clay blocks - cement plaster	-	-	-	-
Partitions - clay blocks - gypsum plaster	-	-	-	-
Frame - steel hot rolled	0.5	5.2	5.2	6.5
Frame - fabricated (fabsec)	-	-	-	-
Frame - RC	-	21.1	42.1	42.1
Frame - RC - reinforcement	-	0.0	0.0	0.0
Frame - timber frame	-	-	-	-
Lift shaft - concrete	7.4	4.9	3.0	2.0
Lift shaft - reinforcement	0.2	0.1	0.1	0.1
Stairs - concrete	10.6	7.1	4.3	2.8
Stairs - reinforcement	0.6	0.4	0.2	0.2

Cavity walls (no render) - cold rolled sections	-	1.2	0.8	-
Cavity walls (no render) - bricks	39.5	32.9	26.3	-
Cavity walls (no render) - bricks - mortar	10.4	8.6	6.9	-
Cavity walls (render) - bricks	13.2	6.6	6.6	-
Cavity walls (render) - bricks - mortar	3.5	1.7	1.7	-
Cavity walls (render) - bricks - render	5.0	2.5	2.5	-
Cavity walls (no render) - stone	-	-	-	-
Cavity walls (no render) - stone - mortar	-	-	-	-
One leaf wall - render	5.0	5.0	-	-
Brick slips - slips	0.6	0.6	-	-
Brick slips - mortar	1.2	1.2	-	-
Metal cladding - cold rolled sections	1.2	2.4	4.8	4.8
Metal cladding - steel pannels	0.9	1.7	3.5	3.5
Metal cladding - aluminium pannels	-	-	-	-
Conrete cladding - cold rolled sections	1.2	1.2	1.2	3.2
Conrete cladding - pannels	2.7	2.7	2.7	7.2
Timber cladding	1.3	0.9	-	-
Curtain wall - steel	-	-	-	-
Curtain wall - aluminium	-	-	-	-
Curtain wall - glass	-	-	-	-
Concrete frame - Render	-	-	-	-
Floor - Timber - beams and floor	3.1	-	-	-
Floor - Timber - plasterboard	1.2	-	-	-
Floor - Timber - gypsum plaster	0.3	-	-	-
Floor - Hollowcore concrete	122.0	34.9	36.6	4.7
Floor - Hollowcore reinforcement	0.8	0.2	0.2	0.0
Floor - Hollowcore topping concrete	69.6	19.9	20.9	2.7
Floor - Hollowcore topping reinforcement	1.1	1.3	0.3	0.2
Floor - Hollowcore cement plaster	6.8	7.8	2.0	1.1
Floor - Hollowcore gypsum plaster	0.5	0.6	0.2	0.1
Floor - flat slab - concrete	122.3	104.8	256.8	342.4
Floor - flat slab reinforcement	3.2	2.8	6.8	9.1
Floor - flat slab - cement plaster	6.8	5.8	14.3	19.0
Floor - flat slab - gypsum plaster	0.5	0.4	1.1	1.4
Floor - composite floor - steel sections	-	5.4	3.8	1.0
Floor - composite floor - steel deck	-	2.9	2.1	0.5
Floor - composite floor - concrete	-	53.9	37.8	9.8
Floor - composite floor - reinforcement	-	0.5	0.4	0.1
Floor - composite floor - plasterboard	-	1.9	1.3	0.3
Floor - composite floor - gypsum plaster	-	0.4	0.3	0.1
Floor - PT slab - concrete	-	-	-	-
Floor - PT slab - reinforcement	-	-	-	-
Roof - timber structure	1.3	-	-	-
Roof - timber structure - plasterboard	0.4	-	-	-
Roof - timber structure - gypsum plaster	0.1	-	-	-
Roof - hollowcore - concrete	11.0	1.8	1.1	0.1
Roof - hollowcore reinforcement	0.3	0.0	0.0	0.0
Roof - hollowcore - topping - concrete	23.2	3.9	2.3	0.2
Roof - hollowcore - topping - reinforcement	0.4	0.3	0.0	0.0
Roof - hollowcore cement plaster	2.1	1.4	0.2	0.1
Roof - hollowcore gypsum plaster	0.2	0.1	0.0	0.0
Roof - flat slab - concrete	46.4	23.2	32.5	27.8
Roof - flat slab - reinforcement	1.1	0.5	0.7	0.6
Roof - flat slab - cement plaster	2.1	1.0	1.4	1.2

Roof - flat slab - gypsum plaster	0.2	0.1	0.1	0.1
Roof - PT - concrete	-	-	-	-
Roof - PT - reinforcement	-	-	-	-
Roof - METSEC - sections	-	0.7	0.3	0.0
Roof - METSEC - panells	-	-	-	-
Roof - aluminium pannels	-	-	-	-
Roof - steel pannels	-	-	-	-
Roof - composite - concrete	-	10.5	4.2	0.7
Roof - composite - reinforcement	-	0.1	0.0	0.0
Roof - composite - steel deck	-	0.6	0.2	0.0
Roof - composite - plasterboard	-	0.3	0.1	0.0
Roof - composite - gypsum plaster	-	0.1	0.0	0.0
Roof Tiles - Plain interlocking concrete tiles	0.8	-	-	-
Roof Tiles - Plain clay tiles	1.1	-	-	-
Roof Tiles - Natural Welsh slates	0.6	-	-	-
Internal doors - steel frame, laminated leaf - leaf	1.2	2.3	2.2	2.1
Internal doors - steel frame, laminated leaf - steel frame	0.7	1.4	1.3	1.3
Internal doors - timber frame, timber leaf	0.6	-	-	-
Internal doors - glass	0.0	0.0	0.0	0.0
External doors - PVC	0.1	0.1	0.1	0.1
External doors - timber frame, timber leaf	0.3	0.3	0.3	0.3
External doors - steel frame, steel leaf	0.5	0.6	0.5	0.5
External doors - glass	0.1	0.1	0.1	0.1
External doors - steel frame, laminated leaf - frame	0.6	0.6	0.6	0.6
External doors - steel frame, laminated leaf - leaf	0.4	0.5	0.4	0.4
Windows - PVC frame	0.9	1.1	1.0	1.0
Windows - PVC, glass	2.0	2.3	2.2	2.1
Windows - timber frame	0.1	-	-	-
Windows - timber, glass	0.1	-	-	-
Windows - aluminium frame	-	-	-	-
Windows - aluminium, glass	-	-	-	-

Table 26: Material quantities for each typology per gross internal floor area - OB, IB, RB, O

Element	OB	IB	RB	O
Foundations - strip concrete	-	-	-	160.1
Foundations - strip reinforcement	-	-	-	1.9
Foundations - piles, caps, beams - concrete	65.3	-	-	20.3
Foundations - piles, caps, beams reinforcement	1.9	-	-	0.7
Foundations - pile raft foundation - concrete	-	-	-	5.9
Foundations - pile raft foundation - reinforcement	-	-	-	0.2
Foundations - pad foundation - concrete	294.3	44.8	156.6	49.4
Foundations - pad foundation - reinforcement	4.4	-	-	0.7
Foundation - retaining walls - concrete	36.5	-	15.4	83.3
Foundation - retaining walls - reinforcement	5.0	-	2.2	2.8
Ground floor - concrete	138.6	585.0	356.3	141.7
Ground floor - reinforcement	2.8	5.2	3.8	6.4
Ground floor - prefab beams	-	-	-	8.1
Ground floor - prefab beams reinforcement	-	-	-	0.4
Ground floor - dense blocks	-	-	-	21.3
Ground floor - screed	58.5	58.5	58.5	40.1
Load bearing walls (cavity) - concrete blocks	16.2	-	6.5	75.5
Load bearing walls (cavity) - concrete blocks - mortar	0.9	-	0.4	12.3
Load bearing walls (cavity) - concrete blocks - cement plaster	2.0	-	2.0	16.7

Load bearing walls (cavity) - concrete blocks - gypsum plaster	2.0	-	2.0	1.5
Load bearing walls (cavity) - clay blocks	-	-	-	-
Load bearing walls (cavity) - clay blocks - mortar	-	-	-	-
Load bearing walls (cavity) - clay blocks - cement plaster	-	-	-	-
Load bearing walls (cavity) - clay blocks - gypsum plaster	-	-	-	-
Load bearing walls (one layer) - clay blocks	-	-	-	-
Load bearing walls (one layer) - clay blocks - mortar	-	-	-	-
Load bearing walls (one layer) - clay blocks - cement plaster	-	-	-	-
Load bearing walls (one layer) - clay blocks - gypsum plaster	-	-	-	-
Load bearing walls - METSEC cold rolled sections	-	-	-	1.5
Load bearing walls - METSEC - plasterboard	2.0	-	2.0	8.8
Load bearing walls - METSEC gypsum plaster	1.0	-	1.0	0.7
Load bearing walls - concrete walls - concrete	33.0	-	8.0	26.2
Load bearing walls - concrete walls - reinforcement	1.0	-	-	0.8
Load bearing walls - concrete walls - cement plaster	2.0	-	2.0	4.4
Load bearing walls - concrete walls - gypsum plaster	0.1	-	0.1	0.3
Steel frame - cold rolled sections	1.0	-	1.0	0.4
Steel frame - plasterboard	0.2	-	0.2	2.3
Steel frame - gypsum plaster	0.1	-	0.1	0.2
Concrete frame - cold rolled sections	1.5	-	1.5	0.9
Concrete frame - plasterboard	2.0	-	2.0	7.4
Concrete frame - gypsum plaster	0.2	-	0.2	0.5
Timber frame - plasterboard	0.1	-	0.1	0.9
Timber frame - gypsum plaster	-	-	-	0.2
Solid wall - bricks	-	-	-	-
Solid wall - bricks, mortar	-	-	-	-
Solid wall - bricks, cememt plaster	-	-	-	-
Solid wall - stone	-	-	-	-
Solid wall - stone, mortar	-	-	-	-
Solid wall - stone, cement plaster	-	-	-	-
Partitions - concrete blocks	20.2	88.7	40.3	73.8
Partitions - concrete blocks - mortar	3.3	14.5	6.6	9.5
Partitions - concrete blocks - cement plaster	5.3	23.2	10.6	20.8
Partitions - concrete blocks - gypsum plaster	0.2	-	0.2	1.3
Partitions - bricks	-	13.1	8.5	7.2
Partitions - bricks - mortar	-	2.4	1.6	1.3
Partitions - bricks - cement plaster	-	-	-	-
Partitions - timber - frame	0.9	-	-	2.1
Partitions - timber - plasterboard	4.1	-	-	3.6
Partitions - timber - gypsum plaster	1.0	-	-	0.8
Partitions - METSEC cold rolled sections	0.5	-	-	1.2
Partitions - METSEC plasterboard	6.2	-	-	7.5
Partitions - METSEC gypsum plaster	1.0	-	-	10.6
Partitions - concrete walls - concrete	2.0	-	-	1.4
Partitions - concrete walls - rebars	0.3	-	-	0.1
Partitions - concrete walls - cement plaster	0.1	-	-	0.3
Partitions - concrete walls - gypsum plaster	0.0	-	-	0.0
Partitions - clay blocks	0.0	-	-	0.0
Partitions - clay blocks - mortar	0.0	-	-	0.0
Partitions - clay blocks - cement plaster	0.0	-	-	0.0
Partitions - clay blocks - gypsum plaster	0.0	-	-	0.0
Frame - steel hot rolled	25.0	54.0	34.8	11.1
Frame - fabricated (fabsec)	0.3	2.0	4.2	2.2
Frame - RC	20.9	-	7.8	11.2

Frame - RC - reinforcement	4.0	-	-	0.3
Frame - timber frame	1.0	-	-	1.7
Lift shaft - concrete	13.2	-	4.3	2.9
Lift shaft - reinforcement	-	-	-	0.0
Stairs - concrete	24.7	-	9.2	4.9
Stairs - reinforcement	-	-	-	0.1
Cavity walls (no render) - cold rolled sections	0.8	-	0.4	0.3
Cavity walls (no render) - bricks	42.9	-	19.3	81.4
Cavity walls (no render) - bricks - mortar	8.0	-	3.6	20.7
Cavity walls (render) - bricks	2.7	-	-	6.7
Cavity walls (render) - bricks - mortar	1.0	-	-	1.8
Cavity walls (render) - bricks - render	0.5	-	-	1.7
Cavity walls (no render) - stone	2.1	-	-	4.3
Cavity walls (no render) - stone - mortar	0.5	-	-	1.1
One leaf wall - render	0.2	-	-	1.3
Brick slips - slips	0.1	-	-	0.3
Brick slips - mortar	0.2	-	-	0.6
Metal cladding - cold rolled sections	-	-	-	1.1
Metal cladding - steel pannels	2.1	4.9	2.2	1.6
Metal cladding - aluminium pannels	1.2	2.1	1.1	1.5
Conrete cladding - cold rolled sections	-	-	-	0.6
Conrete cladding - pannels	-	-	-	1.3
Timber cladding	-	-	-	0.5
Curtain wall - steel	0.9	0.1	0.0	0.3
Curtain wall - aluminium	0.4	0.0	0.0	0.2
Curtain wall - glass	9.7	0.4	0.1	3.4
Concrete frame - Render	-	-	-	-
Floor - Timber - beams and floor	1.5	-	0.7	2.9
Floor - Timber - plasterboard	0.6	-	0.3	1.1
Floor - Timber - gypsum plaster	0.1	-	3.0	0.5
Floor - Hollowcore concrete	61.2	-	27.6	42.3
Floor - Hollowcore reinforcement	0.8	-	0.4	0.4
Floor - Hollowcore topping concrete	20.6	-	10.5	30.4
Floor - Hollowcore topping reinforcement	0.4	-	-	0.6
Floor - Hollowcore cement plaster	1.1	-	0.5	3.1
Floor - Hollowcore gypsum plaster	0.1	-	0.0	0.3
Floor - flat slab - concrete	160.7	-	72.3	88.3
Floor - flat slab reinforcement	7.0	-	-	2.4
Floor - flat slab - cement plaster	7.2	-	2.4	4.6
Floor - flat slab - gypsum plaster	0.5	-	0.2	0.3
Floor - composite floor - steel sections	2.2	-	0.7	1.1
Floor - composite floor - steel deck	2.9	-	17.6	2.2
Floor - composite floor - concrete	55.6	-	1.1	13.2
Floor - composite floor - reinforcement	0.5	-	-	0.1
Floor - composite floor - plasterboard	0.7	-	0.2	0.4
Floor - composite floor - gypsum plaster	0.2	-	0.0	0.1
Floor - PT slab - concrete	194.2	-	27.0	73.8
Floor - PT slab - reinforcement	4.9	-	-	1.6
Roof - timber structure	1.0	-	0.3	5.0
Roof - timber structure - plasterboard	0.1	-	0.0	0.9
Roof - timber structure - gypsum plaster	-	-	-	0.2
Roof - hollowcore - concrete	-	-	-	12.2
Roof - hollowcore reinforcement	-	-	-	0.2
Roof - hollowcore - topping - concrete	-	-	-	13.5

Roof - hollowcore - topping - reinforcement	-	-	-	0.2
Roof - hollowcore cement plaster	-	-	-	1.1
Roof - hollowcore gypsum plaster	-	-	-	0.1
Roof - flat slab - concrete	50.5	-	22.7	16.9
Roof - flat slab - reinforcement	11.1	-	-	1.2
Roof - flat slab - cement plaster	-	-	-	0.5
Roof - flat slab - gypsum plaster	-	-	-	0.0
Roof - PT - concrete	27.6	-	7.6	11.7
Roof - PT - reinforcement	1.0	-	-	0.3
Roof - METSEC - sections	2.8	-	1.3	0.4
Roof - METSEC - panells	1.9	-	0.9	0.9
Roof - aluminium pannels	-	3.8	2.0	1.9
Roof - steel pannels	-	12.8	6.6	6.5
Roof - composite - concrete	2.2	-	-	1.5
Roof - composite - reinforcement	0.0	-	-	0.0
Roof - composite - steel deck	0.1	-	-	0.1
Roof - composite - plasterboard	-	-	-	0.0
Roof - composite - gypsum plaster	0.1	-	0.1	0.0
Roof Tiles - Plain interlocking concrete tiles	-	-	-	6.3
Roof Tiles - Plain clay tiles	-	-	-	8.4
Roof Tiles - Natural Welsh slates	-	-	-	4.2
Internal doors - steel frame, laminated leaf - leaf	0.5	-	0.3	1.1
Internal doors - steel frame, laminated leaf - steel frame	0.7	-	0.3	0.7
Internal doors - timber frame, timber leaf	0.4	-	0.2	0.4
Internal doors - glass	0.0	-	0.0	0.0
External doors - PVC	0.1	-	0.1	0.2
External doors - timber frame, timber leaf	0.1	-	0.0	0.2
External doors - steel frame, steel leaf	0.1	-	0.0	0.3
External doors - glass	0.0	-	0.0	0.1
External doors - steel frame, laminated leaf - frame	0.1	-	0.0	0.3
External doors - steel frame, laminated leaf - leaf	0.1	-	0.0	0.2
Windows - PVC frame	0.6	-	0.3	0.9
Windows - PVC, glass	1.2	-	0.6	1.9
Windows - timber frame	0.2	-	0.1	0.2
Windows - timber, glass	0.2	-	0.1	0.1
Windows - aluminium frame	0.1	-	0.0	0.0
Windows - aluminium, glass	0.2	-	0.1	0.0

8 Range of embodied carbon for different technologies

Table 27: Scenarios to find the lowest and highest embodied carbon for analysed typologies 1/2

Technology	I	II	III	IV	V	VI	VII	VIII	analysed
Domestic buildings									
Element Option	Precast panels	Concrete frame	Steel frame	Cavity walls (E-T,M-T,S-D, D,B,C-F,LRF<4) steel/concrete frame (4≤LRF≤-HRF>10)	Load bearing system (LBS)	Timber frame	Solid wall (E-T,M-T,S-D, D,B,C-F,LRF<4) steel/concrete frame (4≤LRF≤-HRF>10)	One leaf (E-T,M-T,S-D,D B,C-F,LRF<4) Steel frame/LBS	Analysis
Structural system	Precast flat panels	Concrete frame	Steel frame	Concrete blocks; steel frame/concrete	LBS	Timber frame	Bricks; steel/concrete frame	Clay blocks; Steel frame/LBS	mix
Foundations	Pile raft	Piles,caps, beams	Piles,caps, beams	Pile raft	Pads	Pads	Strip foundation; pad foundation	Strip foundation; Piles, caps, beams	mix
Ground floor slab	RC	RC	RC	RC	B&B	B&B	B&B	B&B; RB	mix
External finishing	Render	Concrete cladding	Metal cladding	Bricks (no render/render)	Metal cladding	Timber	Render; metal cladding	Render; metal cladding	mix
Floor	Flat slab	Precast	Composite	Precast	Composite	Timber	Timber; composite	Flat slab; composite	mix
Roof	Flat slab	Precast	Composite	Precast	Composite	Timber	Timber; composite	Flat slab; composite	mix
Roof finishing	Flat roof	Flat roof	Flat roof	Flat roof	Flat roof	Tiles	Tiles; flat	Tiles; flat ,	mix
Partitions	Precast flat panels	Concrete blocks	Concrete blocks	Concrete blocks	Cold rolled sections	Timber	Concrete blocks	Clay blocks; cold rolled sections	mix
Windows	PVC	PVC	PVC	PVC/wooden	PVC/wooden	Wooden	PVC/wooden steel	PVC/timber; PVC/Aluminium	mix
External doors	Steel	Steel	Steel	PVC/wooden	PVC/timber	Wooden	PVC/wooden /Laminated	PVC, wooden; PVC/steel	mix
Internal doors	Laminated	Laminated	Laminated	Laminated/timber	Laminated/timber	Wooden	Laminated/wooden	laminated	mix

Table 28: Scenarios to find the lowest and highest embodied carbon for analysed typologies 2/2

Scenario	I	II	III	IV	V	VI	VII	VIII	analysed
Office buildings									
OLR and OHR share	80/20	80/20	80/20	80/20	50/50	50/50	50/50	50/50	
OLR	Composite beams composite slabs	RC flat slab	Steel frame precast slab	In-situ frame PT slab	Composite beams composite slabs	In-situ frame PT slab	RC flat slab	In-situ frame PT slab	mix
HRO	Composite UB	Composite UB	Composite UB	PT beams and slab	Composite Cellular Plate Girders	PT beams and slab	PT beams and slab	PT beams and slab	mix
Industrial buildings									
Share of SIU/MIU/LIU	0/100/0	100/0/0	50/25/25	0/25/75	0/0/100	50/30/20	0/0/100	50/30/20	mix

Table 29: The lowest and highest embodied carbon for analysed typologies, $kgCO_{2e}/m^2$

Scenario	I	II	III	IV	V	VI	VII	VIII	analysed
E-T	554	434	533	547	423	244	592	353	392
M-T	450	372	449	455	350	216	358	319	309
S-D	526	420	519	527	406	238	586	356	394
D	568	453	568	571	449	246	711	361	433
B	721	544	647	703	496	386	748	504	520
CF	276	223	286	265	209	127	275	139	196
LRF$<$4	470	425	502	510	381	323	454	323	346
4$\leq$LRF$\leq$7	443	430	496	498	421	301	587	482	322
7$\leq$HRF$\leq$10	410	407	470	470	404	261	570	423	344
HRF$>$10	404	407	489	467	409	267	585	431	301
O	423	579	452	491	400	503	563	504	492
IB	436	411	406	383	366	410	463	410	410
RB	370	350	420	463	443	420	370	467	391
Other	554	530	597	604	300	395	717	569	484

9 Floor area added to the building stock

Table 30: Floor area added to the building stock

Typology	2018	
E-T	4,411,918	m^2
M-T	4,443,182	m^2
S-D	8,305,384	m^2
D	3,973,788	m^2
B	491,109	m^2
C-F	2,055,456	m^2
LRF<4,	1,614,121	m^2
4≤LRF≤6	403,530	m^2
7≤HRF≤10	89,564	m^2
HRF>10	22,391	m^2
SUM Domestic:	25,810,444	m^2
OB	2,701,634	m^2
IB	10,548,503	m^2
RB	3,010,749	m^2
O	1,533,733	m^2
SUM Non-domestic:	17,794,619	m^2
SUM All:	43,614,063	m^2

10 Waste rate and transport distances for materials and products used in analysis

Table 31: Waste rate and transport distances for materials and products used in analysis

Material	Waste rate [WR]%	Source	Distance [60] km
Ready mix concrete	5%	[61]	50 km
Precast concrete	1%	[61]	300 km
Reiforcement	5%	[61]	300 km
Concrete blocks	20%	[61]	300 km
Clay blocks	20%	[61]	300 km
Bricks	20%	[61]	300 km
Timber	10%	[61]	1,500 km
Hot rolled steel sections	1%	[61]	300 km
Cold rolled steel sections	4%	[62]	1,500 km
Screed (1:3)	5%	[61]	300 km
Mortar (1:3)	5%	[61]	300 km
Plasterboard	23%	[61]	300 km
Cement plaster (1:4)	5%	[61]	300 km
Gypsum plaster	5%	[61]	300 km
Concrete tiles	20%	analogy to bricks and blocks [61]	300 km
Clay tiles	20%	analogy to bricks and blocks [61]	300 km
Natural slates	20%	analogy to bricks and blocks [61]	300 km
Metal cladding	1%	[63]	1,500 km
Concrete cladding	1%	analogy to precast concrete [61]	300 km
Natural stone blocks	20%	analogy to bricks and blocks [61]	300 km
Fabricated steel sections	4%	[62]	300 km
Glass	5%	[61]	300 km
Aluminium cladding	1%	analogy to metal cladding [63]	1,500 km
Aluminium profiles	1%	[61]	1,500 km
Steel deck	3%	[62]	300 km
PVC windows and doors - frame	N/A	N/A	1,500 km
Timber windows and doors - frame	N/A	N/A	1,500 km
Alu windows and doors - frame	N/A	N/A	1,500 km
External doors - timber frame, timber leaf	N/A	N/A	1,500 km
External doors - steel frame, steel leaf	N/A	N/A	1,500 km
External doors - steel frame, laminated leaf	N/A	N/A	1,500 km
Internal doors - steel frame, laminated leaf	N/A	N/A	1,500 km
Internal doors - timber frame, timber leaf	N/A	N/A	1,500 km

11 Upfront embodied carbon used in this study

All definitions in this paper are in line with the 2021 Carbon Definitions for the Built Environment, Buildings and Infrastructure report published by WLCN, LETI and RIBA [64]. Analysis in this study covers materials and construction processes up to practical completion (Modules A1-A5 according to BS EN 15643-1:2010 [65],[64], upfront embodied carbon [64]).

12 Mass and embodied carbon intensity by component

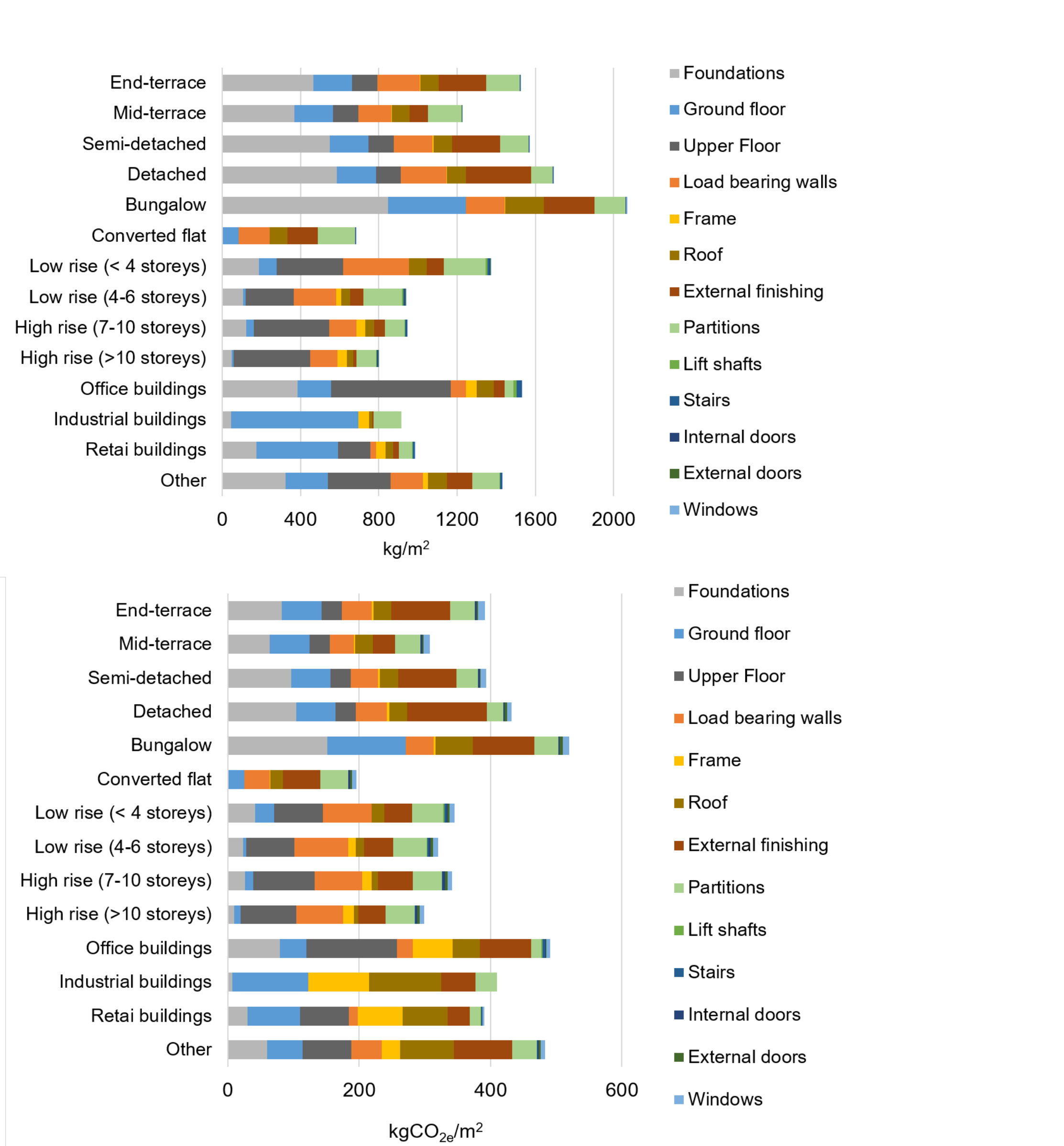


Figure 13: Mass and upfront embodied carbon by use for analysed typologies

The share of upfront embodied carbon per m^2 for building elements is similar to the weight distribution (Fig. 13). For low rise domestic buildings the ratio is between 0.25-0.26. With increase in height, the ratio increases from 0.25 for LRF<4 to 0.37 for HRF>10. For office buildings and other buildings the ratio is

Table 32: Upfront carbon for materials used for this study.

Material	Module A1-A3 $kgCO_2eq/t$	Module A4 $kgCO_2eq/t$	Module A5(+w) $kgCO_2eq/t$	Sum (rounded)
Ready mix concrete[a]	126.0 [66]	5.3	5.1 [67]	136.4
Precast concrete[b]	184.0 [68]	32.0	10.0 [68]	226.0
Reinforcement	1,990.0 [66]	32.0	112.0 [68]	2,134.0
Concrete blocks	93.0 [66]	32.0	9.8 [69]	134.8
Bricks	213.0 [66]	32.0	70.5 [70]	315.5
Clay blocks[f]	109.0 [71]	159.8	9.8 [69]	278.6
Timber[c]	263.0 [66]	159.8	89.8 [72]	512.6
Hot rolled steel sections	1,550.0 [66]	32.0	23.0 [68]	1,605.0
Cold rolled steel sections[d]	2,570.0 [66]	159.8	23.0 [68]	2,752.8
Screed (1:3)	200.0 [66]	32.0	106.5 [73]	338.5
Mortar (1:3)	200.0 [66]	32.0	106.5 [73]	338.5
Plasterboard	260.3 [74]	32.0	36.6 [74]	328.9
Cement plaster (1:4)	163.0 [66]	32.0	106.5 [73]	301.5
Gypsum plaster	102.0 [75]	32.0	47.7 [75]	181.7
Plain interlocking concrete tiles[e]	206.0 [76]	32.0	8.7 [77]	246.7
Plain clay tiles[e]	291.0 [76]	32.0	8.7 [77]	331.7
Natural Welsh slates[e]	63.0 [78]	32.0	8.7 [77]	103.7
Metal cladding	4,370.0 [63]	159.8	68.0 [63]	4,597.8
Concrete cladding	277.0 [79]	32.0	5.7[79]	314.0
Natural stone blocks[f]	60.0 [78]	32.0	9.8 [69]	101.8
Fabricated steel sections	2,461.0 [68]	32.0	23.0 [68]	2,516.0
Glass[g]	1,627.0 [66]	32.0	12.0 [80]	1,671.0
Aluminium cladding[h]	13,000.0 [66]	159.8	5.3 [81]	13,165.1
Aluminium extruded profiles[i]	13,200.0 [66]	159.8	35.6 [43]	13,395.4
Steel deck	2,517.0 [66]	32.0	23.0 [68]	2,572.0
External doors PVC - frame[j]	3,300.0 [78]	159.8	35.6 [40]	3,495.4
External doors - timber frame, timber leaf[k]	924.5 [41]	159.8	33.4 [42]	1,117.7
External doors - steel frame, steel leaf	2,280.0 [42]	159.8	33.4 [42]	2,473.2
External doors - steel frame, laminated leaf	1,403.2 [42]	159.8	33.4 [42]	1,596.4
Internal doors - steel frame, laminated leaf	1,403.2 [42]	159.8	33.4 [42]	1,596.4
Internal doors - timber frame, timber leaf[k]	924.5 [41]	159.8	33.4 [42]	1,117.7
Windows - PVC frame [j]	3,300.0 [78]	159.8	35.6 [40]	3,495.4
Windows - timber frame[j]	665.5 [82]	159.8	35.6 [40]	860.9
Windows - aluminium frame[j]	13,200.0 [66]	159.8	35.6 [40]	13,395.4

[a] Carbon values for ready-mix concrete were taken as a weighted average for ready-mix concrete shares in 2018 [3] (<C16/20 - 11%, C16/20-C20/25 - 25%, C25/30-C30/37 - 54%, >C35/45 - 10%) and A1-A3 carbon values from [66],
[b] Assumed C40/50 with CEM I,
[c] Timber, softwood - carbon storage not included,
[d] Steel cold rolled coil 2.53 $kgCO_2eq/kg$ [66] + conversion to rolled sections 0.04$kgCO_2eq/kg$ [83],
[e] Module A5 - analogy to [77],
[f] Module A5 - analogy to concrete blocks [69],
[g] Flat glass, double glass, 6/16/6mm, 1m^2=30kg,
[h] Assumed 8.5kg PVC profile per m^2 of windows and doors [40],
[i] Assumed 21.6 kg of timber profile per m^2 of windows and doors [82], timber - softwood - carbon storage not included, Module A5 - analogy to PVC windows [40],
[j] Assumed 7.1 kg of aluminium profile per m^2 of window [43], Module A5 - analogy to PVC windows [40],
[k] Module A5 - equivalent to [42].

0.32-0.34, for industrial and retail buildings it increases to 0.40 and 0.44, respectively. The greater the ratio, the lighter the building with a higher upfront embodied carbon.

One-third of the weight and between 20-25% of the upfront embodied carbon per m^2 of two storey dwellings (E-T, M-T, S-D, D) are foundations. For bungalow the share increases to 41% by weight and 30% by embodied carbon. For multi-family residential buildings the share decreases with a height from 12% for LRF<4 to 5% in HRF>10. If we consider jointly foundations and ground floor, the share is between 34-40% for two storey dwellings (E-T, M-T, S-D, D) and reaches 52% for bungalows. For multi-family residential buildings the share decreases with height from 20% to 7% per m^2. As the height of domestic buildings increases, the share of upfront carbon per m^2 for walls and frame (with external finishing) as well as upper floor increases. For low rise single and two family houses (E-T, M-T, S-D, D, B) the share of walls in upfront embodied carbon per m^2 is between 23-26% for M-T and B, 33-40% for E-T, S-D and LRF<4. Share of walls and frame (with external finishing) is the highest for bungalows - 50%. For multi-family residential buildings more than 6 floors, it remains on the similar level - 41-43%. Upper floors are 7-10% for E-T, M-T, S-D, D and 21-28% per m^2 for residential buildings (the share increases with a height).

13 Existing estimates of UK construction material use in 2018

Table 33: Existing estimates of UK construction material use in 2018

Material	Mt	Source	Comment
Constructional steelworks	0.9	BCSA[a][2]	rolled sections, fabricated sections, hollow sections and light sections; 77% - non-domestic buildings; infrastructure - 17%; agriculture, domestic buildings and other - 2%
Cement	11.7	MPA[b][6]	78% home delivered; 55% used in ready-mix concrete (RMC), 25% ‘Products’, 17% ‘Merchant’, the rest -‘Other’
Cementitious materials	3.5	MPA[b][6]	fly ash (FA) and Granulated Ground Blast Furnace Slag (GGBS)
Reinforced steel	0.9	TCC [10]	imports - 0.5 Mt [9], no information on the end of use
Concrete	90	ERMCO[d] [3]	61% - RMC, 55% - buildings, 25% - infrastructure, 5% - concrete roads, 5% - pavements, 10% - other use; the average cement content in RMC - 278 kg/m^3, the average supplementary cementitious materials (SCMs) in RMC - 70 kg/m^3
Concrete blocks	9	BEIS[d] [4]	total consumption
Bricks	5.5	BEIS[d] [4]	total consumption
Sawn softwood	0.5	TTF[f][12] SI Section 1	consumption of timber and panel products - 17.2 Mm^3, sawn and planed softwood - 10 Mm^3; 63% imported

[a] The British Construction Steel Association
[b] Mineral Products Association
[c] Mineral Products Association - The Concrete Centre
[d] The Ready Mixed Concrete Organization
[d] Department for Business, Energy and Industrial Strategy
[f] The Timber Trade Federation

14 Raw data for Figures 5 and 6 included in the paper “Mapping material use and embodied carbon in UK construction”

Raw data for Figures 5 and 6 included in the paper “Mapping material use and embodied carbon in UK construction” are under the link: `https://doi.org/10.5518/1176`.

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References

[1] Material footprint in the UK: 2018. https://bit.ly/3t4FOSM, accessed 04/01/2022.

[2] BCSA Annual Review 2020-2021. Technical report, British Construction Steel Association, 2021. https://bit.ly/3DyNoJ1, accessed 30/12/2022.

[3] Ready-mixed concrete industry statistics. Report, European Ready Mixed Concrete Organization 2018, 2019. https://bit.ly/3x0LQSG.

[4] Monthly Statistics of Building Materials and Components. Technical report, Department for Business, Energy and Industrial Strategy, 2022. https://bit.ly/3jETuRZ, accessed 30/12/2022.

[5] Embodied CO_{2e} of UK cement, additions and cementitious material, Fact Sheet 18. MPA. https://bit.ly/3tXAy1y.

[6] Annulal Cementitious 2001 onwards. Mineral Product Associacion (MPA). https://bit.ly/3ztc2Xi accessed 5/04/2022.

[7] Shanks W., Dunant C.F., Drewniok M.P., Lupton R.C., Serrenho A., and Allwood J.M. How much cement can we do without? Lessons from cement material flows in the UK. *Resources, Conservation and Recycling*, 141:441 – 454, 2019.

[8] English Housing Survey, Household Data. [data collection]. UK Data Service. SN: 8669. http://doi.org/10.5255/UKDA-SN-8669-1, accessed 2/02/2022.

[9] PRODCOM statistics. https://ec.europa.eu/eurostat/web/prodcom, accessed 05/04/2022.

[10] Communication with the Concrere Concrete Centre. May 2022.

[11] TTF Annual Statistical Review 2019. Industry Facts & Figures For 2018. Report, TIMBERTRENDS & Timber Trade Federation, 2019.

[12] Moore N. Timber Utilisation Statistics 2015 for the Forestry Commission. Report, TIMBERTRENDS, 2015. https://bit.ly/3NnwK27, accessed 5/05/2022.

[13] UK's carbon footprint. Annual greenhouse gas and carbon dioxide emissions relating to UK consumption. Report, DEFRA, 2020. ://bit.ly/3sTvH23.

[14] Final UK greenhouse gas emissions national statistics: 1990 to 2019. Technical report, BEIS, ONS, 2021. https://bit.ly/3Tb8CTe, accessed 10/06/2022.

[15] The Sixth Carbon Budget, The UK's path to Net Zero. Report, Committee on Climate Change, 2020. https://bit.ly/3DCmboC, accessed 5/04/2022.

[16] The Sixth Carbon Budget, Buildings. Technical report, Committee on Climate Change, 2020. https://bit.ly/3UpOTjk, accessed 5/04/2022.

[17] The Sixth Carbon Budget, Manufacturing and Construction. Report, Committee on Climate Change, 2020. https://bit.ly/3Wr6sBv, accessed 5/04/2022.

[18] Giesekam J., Steele K., and Hurst T. Green Construction Board Low Carbon Routemap for the Built Environment - 2015 Routemap Progress Technical Report. Report, Arup, Green Construction Board, 2015.

[19] Climate Change. UKGBC's vision for a sustainable built environment is one that mitigates and adapts to climate change. Technical report, UKGBC, 2020. https://www.ukgbc.org/climate-change/, accessed 3/05/2022.

[20] Green A., Jonca A., Spurrier T., Pountney Ch., Giesekam J., Stelle K., et al. Net Zero Whole Life Carbon Roadmap. Technical report, UKGBC, 2021. https://bit.ly/3zQyyLB.

[21] UN. Probabilistic Population Projections Rev. 1 based on the World Population Prospects 2019 rev. 1. Report, United Nations, Department of Economic and Social Affairs, Population Division, 2019. http://population.un.org/wpp/, accessed 3/02/2022.

[22] OnTheMarket. End of terrace house, 3 bedrooms Gosford. https://www.onthemarket.com/details/9864810/, accessed 05/06/2021.

[23] PrimeLocation. Semi-detached house, 3 bedrooms. https://www.primelocation.com/new-homes/details/53520580, accessed 10/06/2021.

[24] rightmove. Detached house, 4 bedrooms, Mill Road, Cambridge. https://bit.ly/3dYtgDG, accessed28/07/2020.

[25] Arnols Keys. Bungalow, 2 bedrooms. https://bit.ly/3l98t53, accessed 05/05/2021.

[26] OnTheMarket. 2 bedrooms flat, Maldon and Ambersham. https://www.onthemarket.com/details/8154167/, accessed 01/04/2021.

[27] NHBC Standards 2021. NHBC, 2021. https://nhbc-standards.co.uk.

[28] Dunant C.F., Drewniok M.P., Orr J.J., and Allwood J.M. Good early stage design decisions can halve embodied CO_2 and lower structural frames' cost. *Structures*, 33:343–354, 2021. https://doi.org/10.1016/j.istruc.2021.04.033.

[29] Transforming Buildings. Technical report, Expedition Engineering, 2010. https://bit.ly/2YtOLZb, accessed 2/02/2022.

[30] Cost of structural steelwork. https://bit.ly/34tb0Bi, 1/05/2019, 2017.

[31] The Concrete Centre - MPA. Cost and Carbon: Concept V4. https://bit.ly/3tIUQMq, year = 2020, type = The Concrete Centre.

[32] Metsec plc. Load Bearing Solutions - Metsec SFS. https://bit.ly/3EK8sLZ.

[33] Wood For Good, Lifecycle Database, PE International. Timber Frame - Closed Panel System. https://bit.ly/3rOuwRU.

[34] Kingspan. Product: KS1200 AB – Insulated Panel System - Product Data Sheet. https://bit.ly/3Izpizo.

[35] Aggregate Industries. BRADSTONE - Reconstituted walling portfolio. https://bit.ly/3yc9rCe.

[36] ACJ Group. Standard Roof Truss. https://www.acj-group.co.uk/standard-roof-truss/.

[37] BuildIt - Self-Build, Renovation, Extension. How to Cost your Roof Tiles. https://bit.ly/31J6eOJ.

[38] Target Fixings. Tile Weight Guides. https://bit.ly/3oIggII.

[39] Wood For Good, Lifecycle Database, PE International. Timber Frame - Open Panel System. https://bit.ly/3DFAIOM.

[40] Environmental and Health Product Declaration - PVC-U plastic windows with the dimensions 1.23 x 1.48 m and insolated double-glazing. European PVC Window Profiles and Related Building Products Association ivzw. https://bit.ly/37a1QaJ.

[41] Environmental and Health Product Declaration - Wooden door. DALOC. https://bit.ly/3ywjukU.

[42] Environmental and Health Product Declaration - Legion / UltraDor Door. ASSA ABLOY, INC. https://bit.ly/3A1bBnT.

[43] Environmental and Health Product Declaration - Aluminium Window System. KAWNEER. https://bit.ly/3m3OO6F.

[44] Non-domestic rating: stock of properties including business floorspace. Valuation Office Agency, ONS, 2019. https://bit.ly/3SWK8gl.

[45] Steel Insight #03, Comparative Cost Study - Multi-storey Offices. BCSA, 2012. https://bit.ly/3a1wqo7, accessed 4/01/2022.

[46] NA+A2:14 to BS EN 1992-1-1:2004+A1:2014. UK National Annex to Eurocode 2: Design of concrete structures. General rules and rules for buildings, 2014.

[47] BS EN 1992-1-1:2004+A1:2014. Eurocode 2: Design of concrete structures. General rules and rules for buildings. BSI, 2014.

[48] BS EN 1993-1-1:2005,Eurocode 3: Design of steel structures. General rules and rules for buildings. British Standards Institution, 2005.

[49] NA+A1:2014 to BS EN 1993-1-1:2005+A1:2014, UK National Annex to Eurocode 3: Design of steel structures. General rules and rules for buildings. British Standards Institution, 2014.

[50] Kingspan. King Zip IP Standing Seam Insulated Panel KS1000 ZIP IP Data Sheet. https://bit.ly/3EXPi4o.

[51] MacKay D., Bock M., Cebon D., Cullen J., Doig K., Gustafsson J., Guthrie P., Hibbert A., Smith S., Swallow P., Symons K., and Williams B. Technical report: Energy cost metric. energy design guide for the civil engineering building in west cambridge, 2018. https://doi.org/10.17863/CAM.52920.

[52] AECOM, editor. *Spon's Architects' and Builders' Price Book 2017*. CRC Press, 2016.

[53] Steel buildings, no. 35/03. BCSA, SCI, 2003. https://bit.ly/3iwvHjL, accessed 3/01/2022.

[54] Single storey industrial buildings. BCSA, SCI, 2018. https://bit.ly/3orBcnw.

[55] Technical specifications. Euroseam standing seam roofing systems. Euroclad Limited. https://bit.ly/361pZ6q.

[56] EPD roller shutters and roller grilles, sectional doors. NASSAU. https://bit.ly/3PqW60X.

[57] Annual Cement Channel of sale 2003 - 2017. MPA, 2020. https://bit.ly/3Bfqkwq.

[58] UK Statistics on Waste. DEFRA, 2021. https://bit.ly/3DamFRh, accessed 20/06/2022.

[59] NFDC waste survey. Technical report, National Federation of Demolition Contractors, 2019.

[60] RICS professional standards and guidance: Whole life carbon assessment for the built environment, rics. Report, RICS, 2017 2017.

[61] Welcome to the Net Waste Tool. WRAP, 2020. https://carbon.tips/nwtool, accessed: July 2020.

[62] Ley J. *An environmental and material flow analysis of the UK steel construction sector*. PhD Thesis, University of Wales, Cardiff University, 2003.

[63] Environmental Product Declaration Wall Panels. KINGSPAN. https://bit.ly/3hUzoje.

[64] Anderson J., Bagenal George C., Bowles L., Desai K., Drewniok M.P., Edwards M., J. Giesekam, Hamot M., Hopkins B., Smith M., Sturgis S., and Wyatt S. Improving consistency in whole life carbon assessment and reporting, carbon definitions for the built environment, buildings and infrastructure. Report, WLCN, LETI, RIBA, 2021. https://bit.ly/3xWVh79.

[65] BS EN 15643:2010 - Sustainability of construction works. Sustainability assessment of buildings. General framework, October 2010.

[66] Inventory of Carbon & Energy - ICE, v3.0 beta - 9 August 2019. Circular Ecology Ltd. http://www.circularecology.com, accessed 10/10/2021.

[67] UK manufactured generic ready-mixed concrete. British Ready-Mixed Concrete Association (BRMCA). https://bit.ly/3DvWgxw.

[68] M.P. Drewniok, J. Campbell, and J. Orr. The lightest beam method–a methodology to find ultimate steel savings and reduce embodied carbon in steel framed buildings. In *Structures*, volume 27, pages 687–701. Elsevier, 2020.

[69] Environmental Product Declaration - UK Manufactured Precast Concrete Blocks. British Precast. https://epd-online.com/PublishedEpd/Download/9477.

[70] Environmental Product Declaration - BDA Generic Brick. The Brick Development Association. https://bit.ly/3yaJamV.

[71] Environmental Product Declaration - Porotherm blocks. Weinerberger s.r.o. https://bit.ly/3I7KID9.

[72] Environmental Product Declaration - $1m^3$ of kiln dried planed or machined sawn timber used as structural timber. Wood for Good. https://woodforgood.com/assets/Downloads/EPD/BREGENEPD000124.pdf.

[73] Environmental Product Declaration - Modified mineral mortars, group 2. FEICA- Association of the European Adhesive and Sealant Industry. https://www.ardexbuildingproducts.ie/wp-content/uploads/2020/09/ARDEX-A-29-EPD.pdf.

[74] Environmental Product Declaration In accordance with EN 15804 and ISO 1402 - Gyproc WallBoard. Saint-Gobain Construction Products UK Limited. https://bit.ly/3iBMfpx.

[75] Environmental Product Declaration In accordance with EN 15804 and ISO 1402 - Gyproc Finish Plaster. Saint-Gobain Construction Products Ireland Limited. https://portal.environdec.com/api/api/v1/EPDLibrary/Files/f1ed6e3b-6ccb-4a0b-b9aa-08d8cda02dc5/Data.

[76] PAS 2050 Assessment of Concrete and Clay Roof Tiles (Plain and Interlocking). Report, Monier (UK) Limited, Ove Arup & Partners Ltd, 2019.

[77] Environmental and Health Product Declaration - Clay roofing tiles in accordance with EN 1304. AGC Glass Spanish Association of Clay Brick and Roofing Tile Manufacturers (HISPALYT). https://bit.ly/3ygFbWc.

[78] Hammond G. and Jones C. Inventory of carbon & energy (ICE) version 2.0. *University of Bath*, 19:20, 2011.

[79] UK manufactured single leaf concrete cladding panel. British Precast Ltd. https://bit.ly/3vej2al.

[80] Environmental and Health Product Declaration - Low-e magnetron coated glass. AGC Glass Europe. https://bit.ly/3kYOZQz.

[81] Environmental Product Declaration - Aluminium FC Facade System - Kalzip. Kalzip GmbH. https://bit.ly/3i6NPAT.

[82] Environmental and Health Product Declaration - Fixed wooden window frame, painted, Accoya, sustainable forestry, NBvT. Nederlandse Branchevereniging voor de Timmerindustrie (NBvT). https://bit.ly/3fjufPS.

[83] The Environmental Impacts of Steel. voestalpine Metsec plc. https://bit.ly/3BDmb66.