Mapping material use and embodied carbon in UK construction

Michał P. Drewniok[a,*], José Manuel Cruz Azevedo[c], Cyrille F. Dunant[c], Julian Allwood[c],
Jonathan M. Cullen[c], Tim Ibell[b], Will Hawkins[b]

[a] *School of Civil Engineering, Faculty of Engineering and Physical Sciences, University of Leeds, Leeds*
[b] *Department of Architecture and Civil Engineering, University of Bath, Bath, UK*
[c] *Department of Engineering, University of Cambridge, Cambridge, UK*

Abstract

The embodied carbon of UK construction is estimated at 43 $MtCO_{2e}$, with 80% from material production and on-site activities. This value has previously been calculated using a multi-region input-output model which models consumption-based emissions using a top-down approach. However, no detailed information exists on the specific material inputs and their related embodied emissions. In this paper, for the first time, uses a bottom-up approach to give much more detailed breakdown of estimates of material use and carbon emissions in UK construction. Ten residential and five non-residential building typologies were analysed and scaled to cover the UK. The scope includes steel, cement & concrete, clay products, timber, glass, plastic, aluminium, stone and gypsum products. We find that 84 Mt of materials were used to deliver the shell and core of buildings and infrastructure, with an embodied carbon of almost 22 $MtCO_{2e}$. Approximately 14.5 Mt and almost 3.6 $MtCO_{2e}$ (steel and concrete only) was used for external works and refurbishments. Half of the total embodied carbon is from concrete, which is mainly used in foundations, ground floor slabs and upper floor slabs in buildings, as well as infrastructure. For equivalent materials, the differences between bottom-up and top-down analysis is less than 15% for cement and concrete, 20% for steel and bricks (top-down analysis provided lower estimations). This analysis allows identification of the aspects of construction with the highest related embodied carbon emissions, and finds the strategies for their minimisation.

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[*] Corresponding author

1. Introduction

Moving towards net-zero operational energy in buildings and infrastructure, the embodied carbon connected to material extraction, manufacturing and production will approach 100% of total emissions [1, 2]. This significant volume of materials used in the construction sector makes it highly carbon intensive [3]. It is essential to minimise the volume and carbon intensity of materials used in construction to achieve net zero UK construction in 2050 [4, 5, 6, 7, 8].

In 2019, the UK became the first major economy to commit to a 'net zero' target [9]. In April 2021, the UK announced to set in law world's most ambitious climate change target, cutting emissions by 78% by 2035 compared to 1990 levels, including international aviation and shipping emissions [10]. In March 2021 the new London Plan 2021 was accepted that requires Whole Life Carbon Assessments for major developments in London. Decarbonisation in construction, both operation and embodied emissions, moves rapidly towards achieving net-zero by 2050. Apart from decarbonisation of material production, resource efficiency at the heart of industrial strategy is crucial in achieving accepted targets [11]. Detailed analysis of material and embodied carbon flow in construction (bottom-up approach) is crucial to identify areas where required interventions should be taken to reduce carbon emissions.

The method that allows to materials to be traced from extraction, production, consumption, recycling and disposal is Material Flow Analysis (MFA) [12]. Dynamic material flow analysis (DMFA) is frequently used to assess past, present, and future stocks and flows [13]. Previous DMFA research has examined various materials in diverse temporal and spatial scopes, in different levels of detail, and for various ends. The most common methods used in DMFA studies are [14]:

1. Bottom-up approach - where the starting point is an inventory of end-use objects, the amount of material used in these objects are calculated using material intensity coefficients (the amount of a specific material in a single unit of the examined object);
2. Top-down approach - which utilises material inflow statistics to determine additions to stock in a series of time periods, referred to as cohorts;
3. Demand-driven modeling - which utilises socioeconomic indicators, such as population and affluence, to model the demand for specific types of objects over time and thus the required materials for the manufacture or construction of those objects;
4. Remote sensing approaches - which utilises satellite-based readings to identify the locations and intensities of human activity.

The results of a bottom-up account provide a detailed account of the state of the stock. They provide "snapshots" of the DMFA in a single point of time.

Even if a bottom-up approach is more accurate that other methods, due to the complexity, it is likely to be used for smaller areas (e.g. cities), or larger but using approximate, average material intensity coefficients. Müller at al. [13] reviewed sixty dynamic analysis studies of metals flows and stock; only six used a bottom-up approach. For the UK, all five studies conducted used a top-down approach. Tanikawa at al. [14] listed 25 DMFA studies which analysed material stocks including those used in construction, on the global, regional or country, or local levels. Only two studies used bottom-up approach, one of which was used by Tanikawa and Hashimoto [15] to analyse 1849–2004 material stock (buildings) in Salford Quays, Manchester, UK. the material stock included aggregate, cement concrete, mortar, ceramics, wood, glass, steel, aluminum, brick, asphalt, others. Augiseau and Barles [16] collected 31 scientific publications on the joint study of construction material flows and stock with a focus on non-metallic minerals. Eleven studies used a bottom-up approach, none of which were UK focused.

Only a few studies have attempted to understand the flow of materials (MFA) along the UK construction supply chain to quantify the environmental impacts of production, use and disposal. They usually analyse only one type of material. Ley [17], in his thesis, developed an MFA of construction steel in the UK, modelled the amount of end-of-life steel and future predictions from 1998. Ley at al. [18] also determined the total energy, CO_2, and waste emissions from steel construction for 1998. Shanks et al. [19] used MFA to map cement use from raw materials to end use in the UK for 2014, analysed the potential of six material efficiency technologies, and identified over-design as an effective intervention to minimise embodied carbon from cement use. Hibbert et al. [20], also using MFA, presented a breakdown of UK cement sector emissions in 2018 in various categories and identified 75 different technologies that could be used to minimise emissions from cement use. Domenech Aparisi et al. [21] conducted an MFA for plastic in UK (in 2016), finding that 0.6 Mt is used in construction. This is somewhat less than the 0.9 Mt for 2017 found by Drewniok at al. [22] and Cullen at al. [23] using top-down analysis and MFA. Romero Perez de Tudela et al. [24] used a bottom-up approach to quantify timber in existing buildings in the London Borough of Tower Hamlets. All these studies are limited in their scope, either by material, region, or both.

Over the last decade, research has been carried out to establish the material and embodied carbon intensity for different building typologies. These include WRAP ECD [25], Embodied Carbon Benchmark Study, University of Washington [26, 27], ”deQo” (database of embodied Quantity outputs [28, 27]). The embodied calculations were limited to only the production of materials used in buildings. Also, even within the same database, calculations were made using different methodologies (except ”deQo”, where collected data are recalculated, and therefore each building is comparable). De Wolf et al. [29] identified the barriers to the effective measurement and reduction of embodied CO_{2e} in practice including uncertainties in carbon coefficients and methodologies. Pomponi et al. [7] confirmed that cradle-to-gate material emissions are the most significant from the whole life embodied carbon. They found also that a simple cradle-to-gate assessment leaves out 30-40% of a building's whole life embodied carbon emissions. the material and carbon intensity of analysed typologies are not often UK specific and are usually focused on multi-storey residential or office buildings. These typologies represent only 3-5% of new builds by floor area [30, 31], with the remainder being single or two-family houses.

In 2021, the 'Part-Z' proposal was launched advocating for Building Regulations to mandate reporting of embodied carbon [32]. This initiative was mainly driven by the construction industry. Just before the 26th UN Climate Change Conference of the Parties (COP26) in Glasgow the UK Government recognised the importance in reporting on embodied carbon in buildings and infrastructure and set out to explore a maximum level of embodied carbon for new builds in the future [33].

The aim of this paper is to model material inputs to UK construction, quantify their embodied carbon, and thereby identify which areas are crucial for decarbonisation.

The objectives are as follows:

- to use a bottom-up approach to trace material consumption by use in the UK construction in 2018, including steel, cement, timber, glass, plastic, gypsum products, stone and aluminium;
- to quantify embodied carbon emissions (upfront embodied carbon, cradle-to-handover) including product stage, transport from factory to site and construction processes;

The scope includes domestic and non-domestic buildings, as well as infrastructure projects. Due to data availability, the analysis is done for 2018. The results allow the areas in the construction sector with the highest material and carbon intensity to be identified. Furthermore, the material and carbon intensity of the analysed building typologies represents current UK practice, and can therefore be used to draw a UK benchmark for these.

2. Background - Material consumption and related emissions in the UK (official statistics)

2.1. Material use in the UK

According to the Office for National Statistics (ONS), 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) was 569 Mt. Non-metallic materials such as cement, ceramics, glass, limestone, clay, marble, sand and gravel, primarily used in construction, are the largest category used (Fig. 1). The UK is increasingly a net importer of materials – domestic extraction accounted for 40% of material footprint in 1997; by 2018, this had fallen to 27% [34]. China and the European Union (EU) contribute 15 and 12% of the UK's material footprint respectively, nevertheless 30% is from the rest of the world (excluding China, EU, US, Russia, India). In 2018, gross added value to the UK's GDP reached 6.5% (£123 bn), a similar level compared to pre-2008 crisis [35]. The value of construction work increased by

9% annually in 2019, before subsequently dropping by 16% in 2020 due to the Covid-19 pandemic [36]. It is projected that construction output will return to pre-Covid levels by 2022, with underlying starts 3% above 2019 levels [37]. Due to the availability of data, the analysis in this paper is for 2018. Nevertheless, according to market predictions construction output in 2021 will be close to 2018 and therefore can be used to describe current construction market.

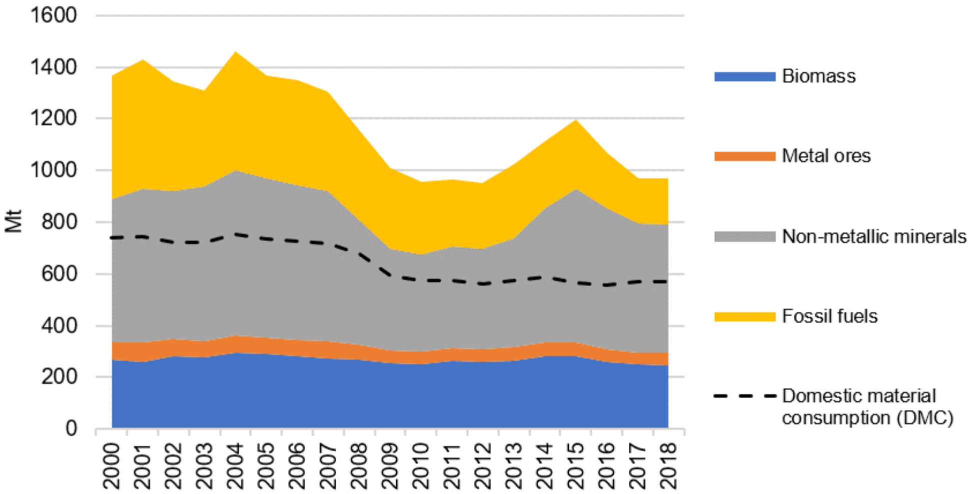

Figure 1: The UK's material footprint by the four constituent material groups and UK's domestic material consumption (DMC) [34]. Data sources: Biomass - Defra, Food and Agriculture Organisation of the United Nations, Eurostat, Kentish Cobnuts Association; Metal ores, Non-metallic minerals - British Geological Survey; Fossil energy materials or carriers - BEIS

Steel, reinforced and unreinforced concrete, timber and clay products are mainly used in the UK for structural purposes. The British Construction Steel Association (BCSA [38]) reported the consumption of constructional steelworks (rolled sections, fabricated sections, hollow sections and light sections) in construction was 0.9Mt in 2018. The largest share of this (77%) was for non-domestic buildings followed by infrastructure projects (17%). Agriculture, domestic buildings and other sectors did not exceed 2%. Of non-domestic buildings, the largest sectors were industrial (64%) and office buildings (15%).

The Ready Mixed Concrete Organization (ERMCO, 2018 [39]) reported that concrete production in the UK was 90 Mt, of which 61% was ready-mix concrete (RMC). More than a half of RMC (55%) was used in buildings (29.7 Mt), 25% 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. 41% of concrete was used as precast (PC), or off-site manufactured concrete. The average cement content in RMC was 278 kg/m^3. ERMCO does not report the average cement content in PC. The total consumption of concrete blocks was approximately 9 Mt [40].

Total UK cement consumption in 2018 was reported as 11.7 Mt (Mineral Products Association, MPA

[41]), 78% of which was produced in the UK [42]. More than a half of cement was used in 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. [19] assessed 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 by 2.2 Mt reaching 15.2 Mt [30].

In 2018, imports of steel reinforcement for concrete were approximately 0.5 Mt [43], with overall consumption approximately 0.9 Mt [44]. No information is available on the end use of steel reinforcement.

According to the "Monthly Statistics of Building Materials and Components" [40], total consumption of bricks in 2018 was approximately 5.5Mt.

The UK's consumption of timber and panel products in 2018 was reported as 17.2 million m^3 [45], 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 [46] reported that 555 thousand m^3 of sawn softwood was used to deliver 177 thousand new houses [30] 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 [46, 30], so keeping this trend we can expect 2018 sawn softwood consumption to be at the level of 970 m^3, equivalent of 0.5 kt. No detailed information is given on what "Other construction" includes and how this consumption has changed since 2015.

The Department for Business, Energy & Industrial Strategy (BEIS) and ONS publish "Monthly Statistics of Building Materials and Component" [40], which list the production and use of materials such as cement and clinker, sand and gravel, concrete and concrete blocks, and bricks. BEIS does not specify where these materials are used.

There is no detailed information on the use of materials used in construction. As a consequence of the increase in net imports of materials, the share of GHG emissions from UK produced goods and services decreased by 7% compared to 1997 while the GHG embedded in imported goods and services stayed constant [47]. With a projected increase in post-Covid construction output, it can be expected that material intensity and embodied carbon will increase compared to 2018 levels [37].

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

2.2. *Emissions in the UK*

The ONS reported the UK's total 2018 GHG emissions as 703 $MtCO_{2e}$ [47], of which 537 $MtCO_{2e}$ are territorial (including international aviation and shipping) [48]. The Sixth Carbon Budget - The UK's path to Net Zero (6CB) [49] - estimated that manufacturing of materials in the UK represented 60 $MtCO_{2e}$, 86% of which were from fuel combustion (for high- and low-grade heat, drying/separation, space heating and on-site electricity generation) and 14% were process emissions (which arise from a range of chemical reactions including the calcination of limestone in cement production). 6 $MtCO_{2e}$ of emissions were from off-road mobile machinery (ORMM), including construction and mining equipment, and ORMM use in transport infrastructure (e.g. harbours, tunnels, bridges) [50].

According to the 6CB, direct and indirect GHG emissions (operation emissions) from buildings were 123 $MtCO_{2e}$, accounting for 23% of UK territorial GHG emissions [51]. UK Manufacturing and Construction [50] emissions were 66 $MtCO_{2e}$. Apart from "Cement and Lime"that is mainly used in construction, the report does not quantify either material use or embodied carbon footprint in UK construction.

The embodied carbon emissions of UK have been estimated over the last decade in a top-down analysis by Giesekam at al. [52, 53] for 2009, 2010, 2012 and 2014. Based on the same methodology, the UKGBC's "Net Zero Whole Life Carbon Roadmap" [3] assessed emission for 2018. Both Giesekam at al. [52, 53] and UKGBC estimations [3] are based on a multi-region input-output model, which underpins the UK consumption-based emissions accounts published annually by Defra as the 'UK's Carbon Footprint'[47]. Both include material extraction, manufacturing, and production as well as construction activities, design services and distribution of people. The total embodied carbon over the last decade is quite constant, being at a similar levels in 2018 and 2010 (Fig. 2). The largest share of embodied carbon in construction by Giesekam at al. [52, 53] was for non-residential buildings at 62%. The share by UKGBC [3] is visible different. For domestic and non-domestic buildings to be similar, at approximately 40% each. The large differences in shares between the two studies result from the inclusion of domestic and non-domestic buildings refurbishments. The share of emissions by source was similar. More than 55% was from material extraction, manufacturing and production, followed by on-site construction activities (Fig. 3). The UK GBC estimated that cement & concrete, timber and steel & other metals alone represent more than 50% (Fig. 4) and approximately 30% of total embodied carbon in construction was imported [3]. The UKGBC study does not disaggregate the use of materials either for new buildings of refurbishment projects.

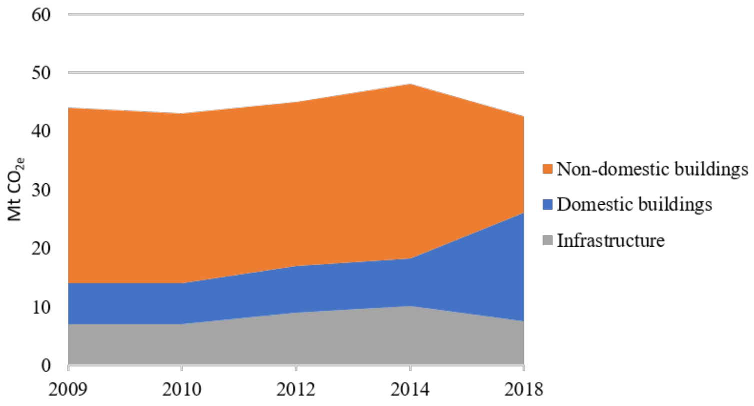

Figure 2: Top-down estimations of embodied carbon in UK construction (2009-2018) [52, 53, 3]

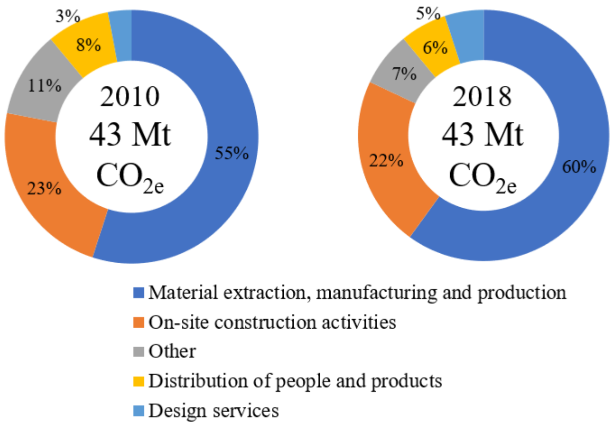

Figure 3: Top-down estimations of embodied carbon in UK construction (2012 and 2018 - 43 MtCO$_{2e}$) [52, 3]

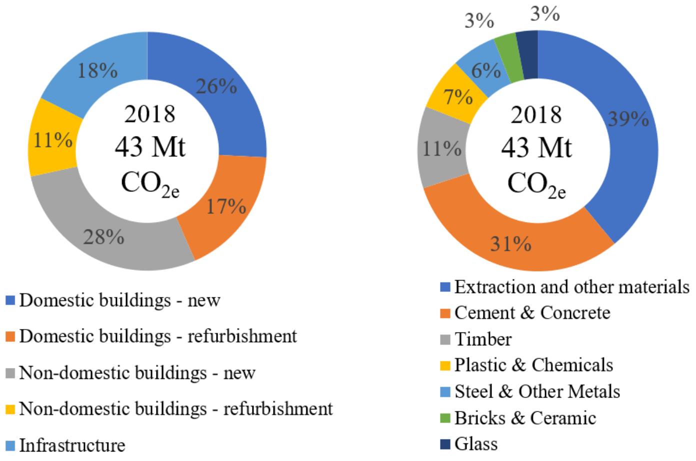

Figure 4: Total embodied carbon share by sector (left), by materials (right) in 2018 [3]

3. Methodology

This paper maps the materials used in construction in 2018 using a bottom-up methodology. The analysis is summarised in Figure 5.

The model includes ten domestic building typologies (detailed in Section 3.1 of this paper and Section 1 of the Supplementary Information (SI) [54]) and five non-domestic building typologies (Section 3.2 and SI, Section 2). The material intensity for each building typology was established by adopting representative case studies. The scope has been limited to the ‘shell and core’, including the superstructure, substructure, façade, doors, windows, partitions as well as walls and ceiling finishes (see example in Fig. 6). Each building typology was designed using the most common UK technologies, with representative proportions of each agreed with input from industrial partners. In this study, cement, steel sections (hot rolled), fabricated sections (from steel sheet), steel reinforcing bar (rebar), cold rolled steel sections (made from steel sheet), steel sheet (steel deck), aluminum sections (extruded aluminum), aluminium sheet, structural timber, clay products, glass, stone products, gypsum plaster, plasterboard, PVC and glass was analysed. Results were then scaled to the annual deliveries reported in the English Housing Survey (EHS) [30] for domestic buildings and The Valuation Office Agency (VOA) [31] for non-domestic buildings and by population to cover the UK market (Fig. 5). Unlike the EHS, the VOA does not provide the annual number of demolitions, and therefore non-domestic buildings demolitions was assessed based on annual demolition waste (Section 3.2.5 reported by the National Federation of Demolition Contractors (NFDC) [55] (more detail can be found in the SI, Section 3). The scope of this study also includes infrastructure and external works (e.g. paving, footpaths, etc.), described in Section 3.3. Due to the limited data for infrastructure and other, material intensity was found using top-down approach based on available data sources (Figure 5).

For UK material used in construction, carbon coefficients for each materials were found from available data sources (Section 3.4). Analysis in this study covers upfront carbon defined as the GHG emissions associated with materials and construction processes up to practical completion (cradle-to-handover, Modules A1-A5 according to BS EN 15643-1:2010 [56] and [57]). These boundaries were chosen as they can represent approximately 55% of whole life embodied carbon emissions for a medium-scale residential building (excluding routine replacement of non-structural components and emissions from demolition and waste processing) [58]. The other reason is that upfront carbon represents the emissions that is spent in the first instance to deliver new buildings by 2050. With a reduction of operational carbon in domestic sector, the importance of upfront embodied carbon will continue to increase. There is a strong belief that new buildings will not be demolished by 2050.

Each material intensity includes material wastage on-site, with specific wastage rates per material as detailed Section 3.4. Material quantities were normalised by gross internal floor area (GIA).

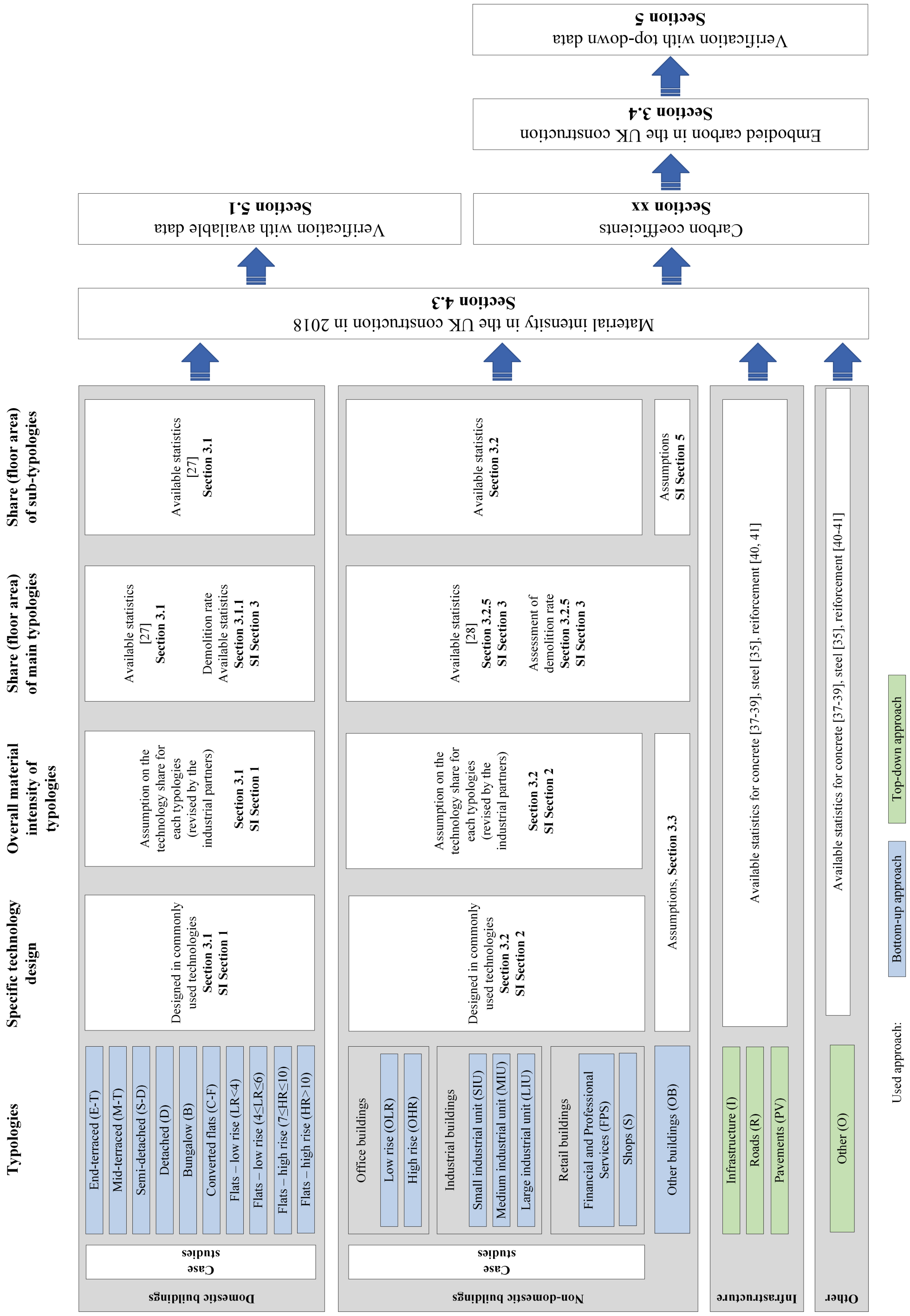

Figure 5: Processes used to find material use and embodied carbon of the UK construction in 2018

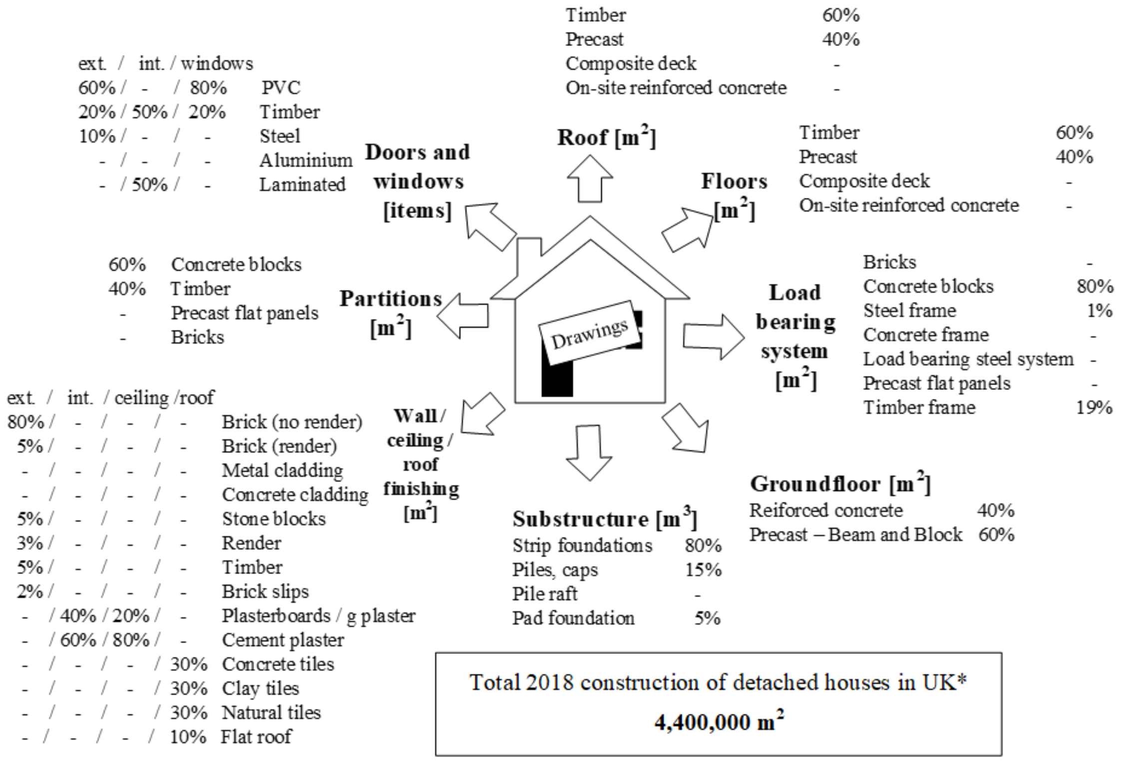

Figure 6: Example of material use assessment for detached house (D) - the same methodology was used for other domestic buildings as well as non-residential buildings.
* typologies share - five year net additions share of typologies in England (2013-2018), calculated floor area for England scaled by population to cover the UK

3.1. Domestic buildings

Over the last 50 years, English dwelling building stock was between 83-84% of the UK domestic building stock. At the same time English population was 83-84% of the UK population [30, 59], therefore there is a good correlation between population and building stock in England and UK. This study covers and analyses the UK territory. When the data for the UK were unavailable, statistics of England, English and Wales or Great Britain were used and were scaled by population.

The material intensity to deliver domestic buildings in the UK was modelled based on the building typologies listed in the 2019 English Housing Survey (EHS) [30], which 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). Case studies to model each of these were chosen to correspond to the average floor area of different typologies [30]. The identified properties had either 2 or 3 bedrooms (SI, Section 1, Table 1). The English Housing Survey [30] distinguishes low rise buildings (up to 6 storeys) and high rise residential buildings (above 6 storeys), however due to use different shares of technologies in low and high rise buildings, these categories were split into 2-4 and 5-6 storeys for low rise buildings and 7-10 and above 10 for high rise residential buildings in this study.

According to the 2019 English Housing Survey [30], approximately 250 thousand new domestic buildings were competed in 2018 (210 thousand in England [30]), 42 thousand were converted to domestic purposes (36 thousand in England [30]). Terraced houses have the largest (38%) share in annual additions to the domestic building stock (2013-2018 average, half end-terraces and half mid-terraced) followed by semi-detached houses and low rise purpose-built flats (up to 6 storeys) at 34% and 13% respectively. The lowest share in annual additions were high rise purpose-built flats (of more than 6 floors) with a share of just 1%.

Table 1: Model buildings used for analysis

Typology	**Code**	EHS [30] **average GIA** m^2	**Model buildings**	**Floor area (GIA)** m^2	**Notes**
End-terrace	E-T	89	3 bedroom	79 [1]	—
Mid-terrace	M-T	88	3 bedroom	79 [2]	End-terrace adjusted to Mid-terrace
Semi-detached	S-D	97	3 bedroom	94[3]	—
Detached	D	149	4 bedroom	132[4]	—
Bungalow	B	77	3 bedroom	76[5]	—
Converted flats	C-F	66	2 bedroom	62	analogy to LRF<4
Purpose built flat low rise up to 4 storeys	LRF<4	58	2 bedroom	62[6]	—
Purpose built flat low rise up to 6 storeys	4≤LRF≤6	58	2 bedroom	62[6]	analogy to LRF<4 adjusted to the height*
Purpose built flat high rise up to 10 storeys	7≤HRF≤10	61	2 bedroom	62[6]	analogy to LRF<4 adjusted to the height*
Purpose built flat high rise above 10 storeys	HRF>10	61	2 bedroom	62[6]	analogy to LRF<4 adjusted to the height*

[1] Source: OnTheMarket [60], assessed 05/06/2021
[2] Source: OnTheMarket [60], assessed 05/06/2021
[3] Source: PrimeLocation [61], assessed 10/06/2021
[4] Source: rightmove [62], assessed 28/07/2020
[5] Source: Arnolds Keys [63], assessed 05/05/2021
[6] Source: OnTheMarket [64], assessed 01/04/2021
* see Tables 3 - 5 in SI

The selected case studies represent current housing trends, being found in early 2021 on letting agencies or developers' websites (SI, Section 1). The height of the analysed case studies are of typical houses and bungalows (Annex Table 1.2: Number of storeys above ground by dwelling type [30]) where 90% of typical houses in England were found to be 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), widows 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 [65] (SI, Section 1.1, Table 1.1). 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 frame) were modelled based on NHBC Standards, structural calculations, guidelines and current practice. For each building typology, the proportions of each viable building technology were assumed and verified by industry partners (SI, Section 1, Table 1.1).

Analysed case studies represent simple shaped buildings. For the purpose of this study we assumed material allowance for shape irregularity. Dunant at al. [66] for non-domestic buildings found that irregular layout (grid) can cause up to 23% of carbon inefficiency (material wastage) in floor structure, and approximately 20% in decking optimisation. For this study we have assumed 10-15% material allowance for floors and roofs, 5-20% for foundations, ground floor, and partitions, 5-10% load bearing walls. Detailed list of assumed material allowances are included in Section 4 included in SI.

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 from the industrial partners, it was 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) with the floor structures and foundations reused, since it is very likely that design floor live loads for these buildings are higher than for domestic purposes. A key driver of conversion from non-domestic to residential purposes is to keep as much existing structure as possible. According to London Crane Survey 2018, almost half of new construction projects in London are refurbishments [67]. Expedition Engineering, in "Transforming Buildings" [68], reported that it was possible to re-use 70% of the original building structure due to refurbishment of non-domestic building for domestic purposes in London. For this study we assumed that foundations and floor slabs are reused in 100%, and structural system (load bearing walls, frame) in 50%. The rest elements are as new.

3.1.1. Assessment of demolition of domestic buildings

Between 2006 and 2018, the annual demolition of domestic buildings in England decreased from 21 to 8 thousand, which scales to 25.1 and 9.5 thousand respectively for the UK. Demolitions were therefore 3% of annual net additions. No information was found about the share of the typology of demolished domestic buildings. In this study, the share demolitions were assumed proportional to share of net additions by floor area for different typologies (Table 2).

3.2. Non-domestic buildings

The Valuation Office Agency (ONS) [31] publish an annual "Non-domestic rating: stock of properties including business floorspace" which includes the number and floorspace of rateable properties in England

Table 2: Share of net additions - average for five years from 2013-2018 [30]

	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%

and Wales. A rateable property (also known as hereditament) 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 3 presents the sectors and sub-sectors included in "Non-domestic rating" as well as assumed typologies.

In 2018 in England and Wales were 2.1m non-domestic properties, 25% were Retail (RB), 25% Industrial (IB), 20% Office (OB) and 30% Other buildings (O). Non-domestic stock floor area was 587m m^2, 56% of which represented IB, 18% RB, 15% OB and 11% other [31]. England and Wales represent 89% of the UK population an therefore the number of non-domestic buildings can be estimated as 2.3m (660m m^2). Compared to 2017, in 2018 the net-addition of non-domestic rateable properties was 60 thousand (2.7m m^2). This 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 3), 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.

3.2.1. Office buildings

Peter Brett Associates (PBA) in [69] have identified and designed representative framing solutions for two typical UK office buildings – a business park office and a city centre office (see SI, Section 2.1). The business park office (labelled OLR in Table 3) has three storeys, a GIA of approximately 3,200 m^2, a structural grid 7.5 x 9m, and a floor-to-floor height of 2.8 m. The city centre office (OHR) has eight storeys, approximately 15,000 m^2 GIA, a 7.5 x 15m structural grid and a floor-to-floor height between 4.18 and 4.38 m depending on structural system. Key design assumptions are included in Table 6 of the SI. PBA designed these buildings in the UK's most commonly used technologies (Table 4). The share of technologies were assumed and

Table 3: Sector and sub-sector categories of non-domestic buildings [31]

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)

verified by industrial partners (SI, Table 7). The material intensities for different technologies were taken from provided take-offs or was modelled individually (see SI, OLR - Tables 8 and 9, OHR - Tables 10 and 11). After Dunant at al. [66], 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 (see SI, Section 4).

Table 4: Office buildings - Framing options from the cost study included in [69]

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

3.2.2. *Industrial buildings*

The Valuation Office Agency (ONS) [31] 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) - were each modeled as steel structures with reinforced concrete pad foundations, curtain walls and lightweight roof with sandwich panels (see SI, Section 2.2). An overview is given in Table 5, and the assumed shares of each type type are presented in Table 12 in the SI.

The material intensities for different buildings were taken either directly from the source (e.g. [70] for SIU), typical material intensity from available sources (e.g. steel use per m^2 for MIU and LIU from [71]) or 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. A detailed list of assumed material allowances are included in Section 4 of the SI. Material intensity for industrial buildings are provided in the SI in Tables 13, 14, 15 for SIU, MIU and LIU respectively.

Table 5: Industrial buildings - case studies

Typology	**Small industrial unit**	**Medium size industrial unit**	**Large size industrial unit**
Code	SIU	MIU	LIU
Source	[70]	[71]	[72]
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%

3.2.3. *Retail buildings*

The Valuation Office Agency (ONS) [31] 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 16 in the SI. Overall material intensity for retail buildings by gross internal floor area (GIA) are included in SI, Section 5.

Table 6: Retail buildings - assumptions

Sub-sector	**Typology**	**Equivalent to**
Financial and Professional Services (FPS)	Low Rise office building (OLR)	Financial and Professional Services (FPS)
Shops (S)	Low Rise office building (OLR)	Shopping centre
	Small size industrial unit (SIU)	Supermarket
	Medium size industrial unit (SIU)	Superstore
	Large size industrial unit (LIU)	Distribution centre

3.2.4. *Other buildings*

The Valuation Office Agency (ONS) [31] divide Other buildings into twelve categories. Due this diversity, in this study a material intensity per m^2 was assumed as an average from all materials (elements) calculated for domestic, Office, Retail and Industrial Buildings (excluding conversions).

3.2.5. *Demolition of non-domestic buildings*

The National Federation of Demolition Contractors (NFDC), which represents 80% of UK demolition works, reported 25 Mt waste from demolition, 80% of which was hardcore [55]. Scaling this figure to cover the UK and using a 92.3% recovery rate gives 32.5 Mt of total waste and 26 Mt of hardcore from demolition. From the information received from NFDC shares of hardcore waste from demolition from infrastructure projects, and buildings are 40% and 60% respectively.

Since 2006, demolition of dwellings decreased from 26,060 to 9,480 in 2018, and is the lowest reported in this period [30]. No data is available on the number of demolitions of non-domestic buildings as well as the number of new non-domestic buildings completions [31]. For the purpose of this study, the number (floor area) of demolitions of non-domestic buildings by typologies were calculated. The downstream hardcore waste data (NFDC) was compared to materials that could be considered as a hardcore waste in the end of their life (concrete, concrete blocks, bricks, etc.). A 'hardcore waste' from new buildings were found for all typologies within domestic and non-domestic buildings (See Table 19 in SI). Detailed calculations are included in Section 3 of SI.

3.3. *Infrastructure and other*

Although non-building construction accounts for a significant proportion of UK material use on construction, 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 is still included in this study, however, in this case already available statistics were used.

For infrastructure, material quantities were calculated for concrete (ready mix-concrete, precast concrete), steel reinforcement and constructional steelworks. The Ready Mixed Concrete Organization (ERMCO 2018 [39]) reported that 25% out of 22.5 million m^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. Other uses of cement such as refurbishment, repairs, extensions and maintenance are not included in RMC statistics, so the the 'Other' category from the Annual Cement Channel of Sale 2003 - 2017 [73] was used in this study with a total mass of 0.55 Mt.

The British Construction Steel Association (BCSA [38]) reported the consumption of constructional steelworks (rolled sections, fabricated sections, hollow sections, light sections) in infrastructure as 146kt and other (incl. agriculture) 37kt. General assumptions for infrastructure, pavements, concrete roads and other are included in Section 2.5, Table 17 of the SI.

3.4. *Carbon calculations*

In this study, embodied carbon for cradle-to-handover (Modules A1-A5) is calculated in accordance with UK standards (EN 15978:2011 [74] and EN 15804:2014 [75]). For each material, the total tonnage is multiplied by the embodied carbon factor presented in Table 7. A wastage rate is also included to account for over-ordering and site errors.

For the purpose of this study, all definitions are in the line with the Carbon Definitions for the Built Environment, Buildings and Infrastructure report published by WLCN, LETI and RIBA [57] in 2021.

It is uncertain how and where the materials and products to deliver new properties are produced, so for the purpose of this study the Inventory of Carbon and Energy (ICE), V3.0 BETA [76] was taken as the main source for carbon coefficients (Module A1-A3). As a result, the carbon coefficients for this study represent world averages. If materials were not listed in the ICE [76], carbon coefficients for Modules A1-A3 were assumed from suitable available Environmental Product Declarations (EPDs). For end products such as windows and doors, relevant EPDs were used.

Transport (Module A4) emissions were calculated individually for each material based on road haulage (average laden) - 0.10650 gCO_2eq/kg/km [77] - using the distances included in Table 8.

Emissions related to construction processes (Module A5), apart from the emissions to deliver new properties, includes emissions from the transportation the waste away from site for reuse or recycling with assumed transport distance 50 km by road (Module A5 (A5+w)). Waste rate for analysed materials were included in Table 8. For all materials waste transportation was assumed as 5 $kgCO_2eq$/t (default assumption from [78]). Processing and disposal of construction waste assumed as 1.3 $kgCO_2eq$/t [58].

Table 7: Upfront carbon for materials used for this study.

Material	**Module A1-A3** kgCO$_2$*eq*/t	**Module A4** kgCO$_2$*eq*/t	**Module A5(+w)** kgCO$_2$*eq*/t	**Sum** (rounded)
Ready mix concrete[a]	126.0 [76]	5.3	5.1 [79]	136.4
Precast concrete[b]	184.0 [80]	32.0	10.0 [80]	226.0
Reinforcement	1,990.0 [76]	32.0	112.0 [80]	2,134.0
Concrete blocks	93.0 [76]	32.0	9.8 [81]	134.8
Bricks	213.0 [76]	32.0	70.5 [82]	315.5
Clay blocks[f]	109.0 [83]	159.8	9.8 [81]	278.6
Timber[c]	263.0 [76]	159.8	89.8 [84]	512.6
Hot rolled steel sections	1,550.0 [76]	32.0	23.0 [80]	1,605.0
Cold rolled steel sections[d]	2,570.0 [76]	159.8	23.0 [80]	2,752.8
Screed (1:3)	200.0 [76]	32.0	106.5 [85]	338.5
Mortar (1:3)	200.0 [76]	32.0	106.5 [85]	338.5
Plasterboard	260.3 [86]	32.0	36.6 [86]	328.9
Cement plaster (1:4)	163.0 [76]	32.0	106.5 [85]	301.5
Gypsum plaster	102.0 [87]	32.0	47.7 [87]	181.7
Plain interlocking concrete tiles[e]	206.0 [88]	32.0	8.7 [89]	246.7
Plain clay tiles[e]	291.0 [88]	32.0	8.7 [89]	331.7
Natural Welsh slates[e]	63.0 [4]	32.0	8.7 [89]	103.7
Metal cladding	4,370.0 [90]	159.8	68.0 [90]	4,597.8
Concrete cladding	277.0 [91]	32.0	5.7[91]	314.0
Natural stone blocks[f]	60.0 [4]	32.0	9.8 [81]	101.8
Fabricated steel sections	2,461.0 [80]	32.0	23.0 [80]	2,516.0
Glass[g]	1,627.0 [76]	32.0	12.0 [92]	1,671.0
Aluminium cladding[h]	13,000.0 [76]	159.8	5.3 [93]	13,165.1
Aluminium extruded profiles[i]	13,200.0 [76]	159.8	35.6 [94]	13,395.4
Steel deck	2,517.0 [76]	32.0	23.0 [80]	2,572.0
External doors PVC - frame[j]	3,300.0 [4]	159.8	35.6 [95]	3,495.4
External doors - timber frame, timber leaf[k]	924.5 [96]	159.8	33.4 [97]	1,117.7
External doors - steel frame, steel leaf	2,280.0 [97]	159.8	33.4 [97]	2,473.2
External doors - steel frame, laminated leaf	1,403.2 [97]	159.8	33.4 [97]	1,596.4
Internal doors - steel frame, laminated leaf	1,403.2 [97]	159.8	33.4 [97]	1,596.4
Internal doors - timber frame, timber leaf[k]	924.5 [96]	159.8	33.4 [97]	1,117.7
Windows - PVC frame [j]	3,300.0 [4]	159.8	35.6 [95]	3,495.4
Windows - timber frame[j]	665.5 [98]	159.8	35.6 [95]	860.9
Windows - aluminium frame[j]	13,200.0 [76]	159.8	35.6 [95]	13,395.4

[a] Carbon values for ready-mix concrete were taken as a weighted average for ready-mix concrete shares in 2018 [39] (<C16/20 - 11%, C16/20-C20/25 - 25%, C25/30-C30/37 - 54%, >C35/45 - 10%) and A1-A3 carbon values from [76],

[b] Assumed C40/50 with CEM I,

[c] Timber, softwood - carbon storage not included,

[d] Steel cold rolled coil 2.53 kgCO$_2$*eq*/kg [76] + conversion to rolled sections 0.04kgCO$_2$*eq*/kg [99],

[e] Module A5 - analogy to [89],

[f] Module A5 - analogy to concrete blocks [81],

[g] Flat glass, double glass, 6/16/6mm, 1m^2=30kg,

[h] Assumed 8.5kg PVC profile per m^2 of windows and doors [95],

[i] Assumed 21.6 kg of timber profile per m^2 of windows and doors [98], timber - softwood - carbon storage not included, Module A5 - analogy to PVC windows [95],

[j] Assumed 7.1 kg of aluminium profile per m^2 of window [94], Module A5 - analogy to PVC windows [95],

[k] Module A5 - equivalent to [97].

Table 8: Waste rate and transport distances for materials and products used in analysis

Material	**Waste rate** [WR]%	**Source**	**Distance [100]** km
Ready mix concrete	5%	[101]	50 km
Precast concrete	1%	[101]	300 km
Reinforcement	5%	[101]	300 km
Concrete blocks	20%	[101]	300 km
Clay blocks	20%	[101]	300 km
Bricks	20%	[101]	300 km
Timber	10%	[101]	1,500 km
Hot rolled steel sections	1%	[101]	300 km
Cold rolled steel sections	4%	[17]	1,500 km
Screed (1:3)	5%	[101]	300 km
Mortar (1:3)	5%	[101]	300 km
Plasterboard	23%	[101]	300 km
Cement plaster (1:4)	5%	[101]	300 km
Gypsum plaster	5%	[101]	300 km
Concrete tiles	20%	analogy to bricks and blocks [101]	300 km
Clay tiles	20%	analogy to bricks and blocks [101]	300 km
Natural slates	20%	analogy to bricks and blocks [101]	300 km
Metal cladding	1%	[90]	1,500 km
Concrete cladding	1%	analogy to precast concrete [101]	300 km
Natural stone blocks	20%	analogy to bricks and blocks [101]	300 km
Fabricated steel sections	4%	[17]	300 km
Glass	5%	[101]	300 km
Aluminium cladding	1%	analogy to metal cladding [90]	1,500 km
Aluminium profiles	1%	[101]	1,500 km
Steel deck	3%	[17]	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

4. Results

4.1. Embodied carbon ranges for each building typology

Figure 7 presents a range of upfront embodied carbon for different technologies. All assumptions are included in Tables 24 and 25 and results in Table 26 in SI. Figure 7 also include embodied carbon for different typologies selected for further analysis, that represent current practice in the UK.

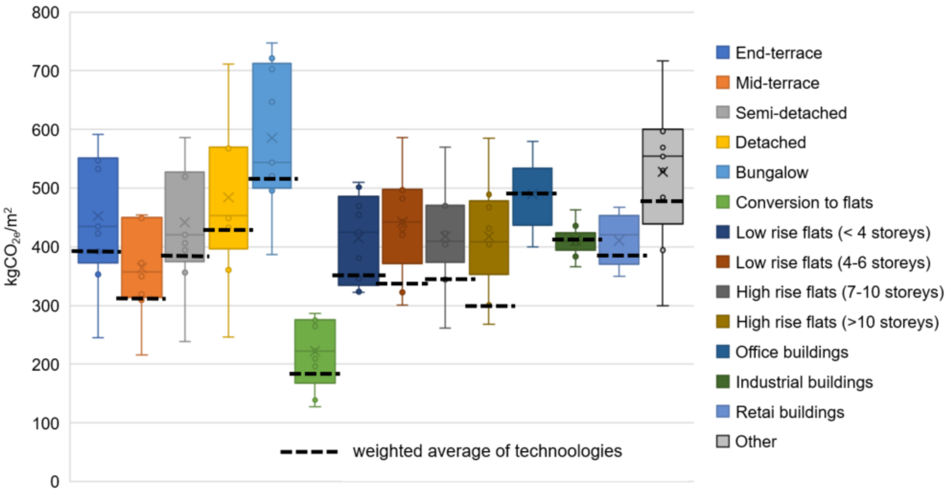

Figure 7: Distribution of embodied carbon for different technologies and embodied carbon for final analysis (based on technology share used in UK construction - see SI, Section 6).
For domestic buildings, 8 technologies were analysed; for low rise office buildings (OLR) - 4 and 3 for high rise office buildings (OHS). For office buildings different share of OHR and OLR was analysed. For industrial buildings (SIU, MIU, LIU), Retail buildings and Other buildings, only the share of typologies within a sector was analysed - see Tables 24 and 25 in SI.

The results demonstrate a wide range of carbon intensities for each typology, based on the materials and technologies used. The highest embodied carbon per m^2 for E-T, M-T, S-D, D, B was found for solid wall construction (VII - SI, Table 7) followed by precast flat panels (I), then cavity walls with concrete blocks (IV). The lowest carbon technologies were timber frame (VI) and one leaf wall with clay blocks (VIII), having approximately 55% and 35% carbon savings respectively compared to cavity walls with concrete blocks (IV). The lowest embodied carbon per m^2 for C-F was for timber frames (VI) and one leaf wall with clay blocks (VIII), approximately 50% lower than for precast panels (I) and cavity walls with concrete blocks (IV).

For typical low rise office (OLR) identified in [69] and assumed above carbon coefficients, the the highest embodied carbon was found for Reinforced concrete flat slab with in-situ columns (IIIa), 600 kgCO$_2e$/m^2, with 80% share from reinforced concrete. The lowest for Steel Composite UB Restricted Depth (IIb), 406 kgCO$_2e$/m^2, with a third of embodied carbon from reinforced concrete and 27% from steel sections. Steel frame and precast concrete slab (IIa) was 10% higher carbon intensive than IIb (440 kgCO$_2e$/m^2), in-situ concrete frame with post tensioned slab (IVa) 20% compared to IIb (480 $kgCO_2e/m^2$). The highest embodied carbon for high rise office buildings (OHR) was found for PT Band Beam and Slab (IIIb), 525 $kgCO_2e/m^2$, with 2/3 share from reinforced concrete. The lowest, Steel Composite Cellular Plate Girders (Ib), 393 $kgCO_2e/m^2$. Almost a third of embodied carbon in Ib was from reinforced concrete and 26% from steel sections. Steel Composite UB Restricted Depth (IIb) was in the middle, with embodied carbon 487 $kgCO_2e/m^2$. 42% and 25% embodied carbon came from reinforced concrete and steel sections, respectively.

Embodied carbon for SIU, MIU and LIU was 411, 435 and 410 $kgCO_2e/m^2$ respectively, giving 418 $kgCO_2e/m^2$ for the weighted average. For RB and Other (OB) the range of embodied carbon was between 350-467 and 300-717 $kgCO_2e/m^2$ respectively. In the next section, more detailed analysis was conducted for the weighted averages of technologies representing current practice in the UK (dashed line on Fig. 7).

4.2. Embodied carbon intensity by component

Figure 8 shows the mass and upfront embodied carbon for each building typology based on the weighted averages of technologies representing current practice in the UK, broken down by component.

The share of upfront embodied carbon per m^2 for building elements is similar to the weight distribution. For low rise domestic buildings the ratio between upfront embodied carbon to overall weight is between 0.25-0.26. For residential buildings, 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 0.32-0.34 but 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 (Fig. 8). 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).

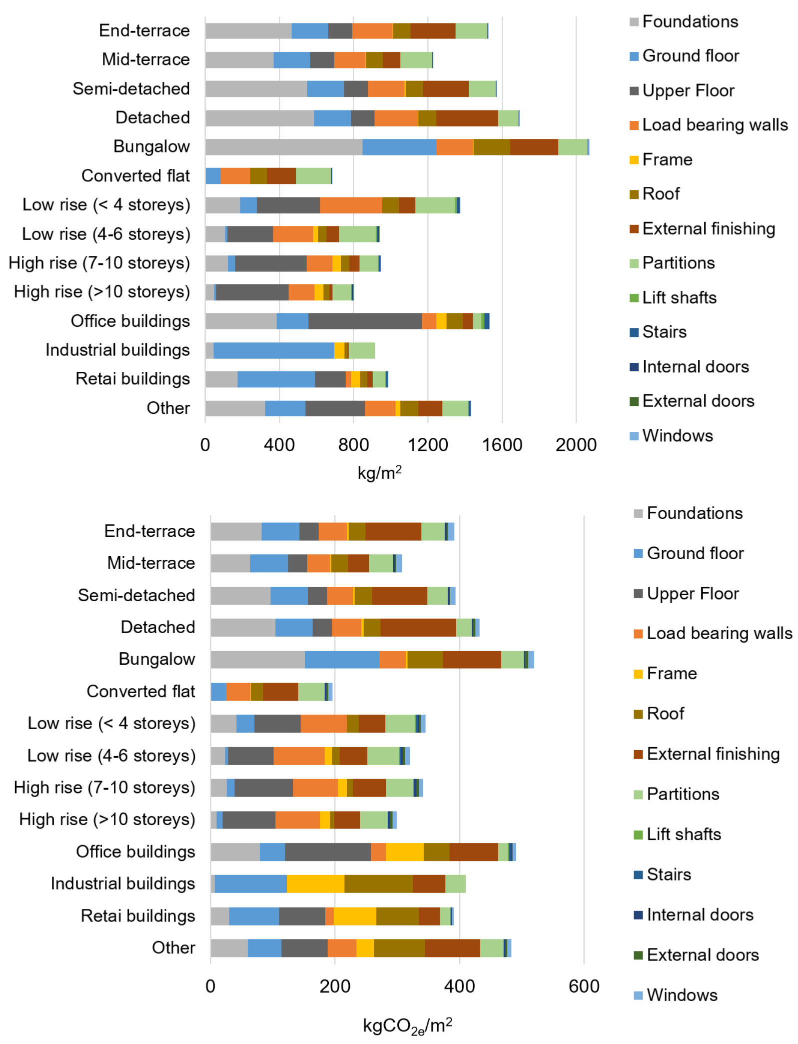

Figure 8: Mass and upfront embodied carbon by use for analysed typologies

Approximately a quarter upfront embodied carbon per m^2 of office buildings (OB) and Other (O) is allocated in foundations and ground floor. This increases to approximately a third for IB and RB. Upper floors are a third of upfront embodied carbon per m^2 for those buildings, except industrial buildings, where did not assume upper floors.

The upfront embodied carbon by material for each building typology is presented in Fig. 9. The least carbon intensive from domestic buildings is C-F followed by HRF>10 and by M-T, the highest B followed by D. Approximately 60% of upfront embodied carbon in domestic buildings (E-T, M-T, S-D, D, B, CF) and 70% for LRF<4 is from cementitious materials, a which of which is either ready mix concrete (RMC) or reinforced precast concrete (PC). For higher than 4 storey residential buildings the share of cementitious materials decreases from 40-30% per m^2. However, the share of RMC and PC increases from 60% up to 90% with a high. Finishing of external walls (external brick layer alone) in single and two family houses (E-T, S-D, D, B) is approximately a 20% of upfront embodied carbon per m^2. The embodied carbon from steel reinforcement for all domestic building typologies except converted flats varied from 11-15%. The highest is for B and LRF<4.

For HR, O, IB, and RB, approximately one third of upfront embodied carbon is from cementitious materials, almost all (90-95%) was from ready mix or reinforced precast concrete. The embodied carbon from steel reinforcement varied from 4% for IB and RB, 10% for O and 23% for office buildings. One third of the upfront embodied carbon in O is from steel sections (hot and cold rolled). For IB, RB and O the share is 25%.

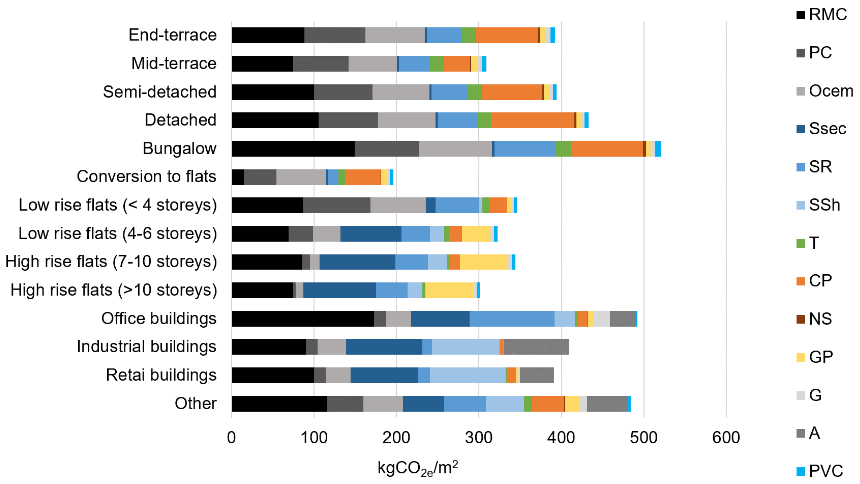

Figure 9: Upfront embodied carbon by material for analysed typologies.
RMC - Ready-mix concrete; PC - Precast concrete (incl. reinforced and unreinforced); Ocem - Other cementitious (incl. mortar, plaster, screed); Ssec - Steel sections (incl. hot, cold rolled, fabricated); SR - Steel reinforcement; SSh - Steel sheet (incl. steel deck, cladding); T - Timber; CP - Clay products (incl. bricks and tiles); NS - Natural stone (blocks, tiles); GP - Gypsum products; G - Glass; A - Aluminium (incl. sections, cladding); PVC - PVC (used for windows and doors).

4.3. Material use and upfront embodied carbon in 2018 UK construction

The total mass and upfront carbon emissions in UK construction for 2018 is shown in Figures 10 and 11 respectively. These show that almost 100 Mt of materials were used with an upfront embodied carbon of 25 Mt CO$_{2e}$. New domestic buildings represent 41% by mass, followed by infrastructure and new non-domestic buildings at 23% and 20% respectively. Almost a third by mass was in foundations and ground floor, 18% in construction elements for infrastructure and 15% other use. More than 80% by total mass was concrete (RMC and PC), 7% other cementitious materials (cement mortar, cement render or screed), and 6% clay products, mainly bricks. The remaining 7% was other materials. A third of all concrete (35%)

was used in domestic buildings, mainly for foundations and ground floor, 28% in infrastructure and 20% in non-domestic buildings, mainly for foundations and ground floor.Three quarter of all other cementitious materials as well as 90% of clay products were used in domestic buildings - 11% of all materials.

In terms of upfront embodied carbon, almost 37% was from new domestic buildings, followed by non-domestic buildings at 30%. One fifth of upfront embodied carbon (22%) was from foundations and ground floors followed by construction elements for infrastructure and external finishing, at 17% and 11% respectively. In terms of materials, embodied carbon is dominated by concrete. Half of the upfront embodied carbon was concrete (RMC and PC), 24% steel, including steel sections, steel reinforcement and steel sheets. The share of other cementitious materials and clay products was 9% and 7%.

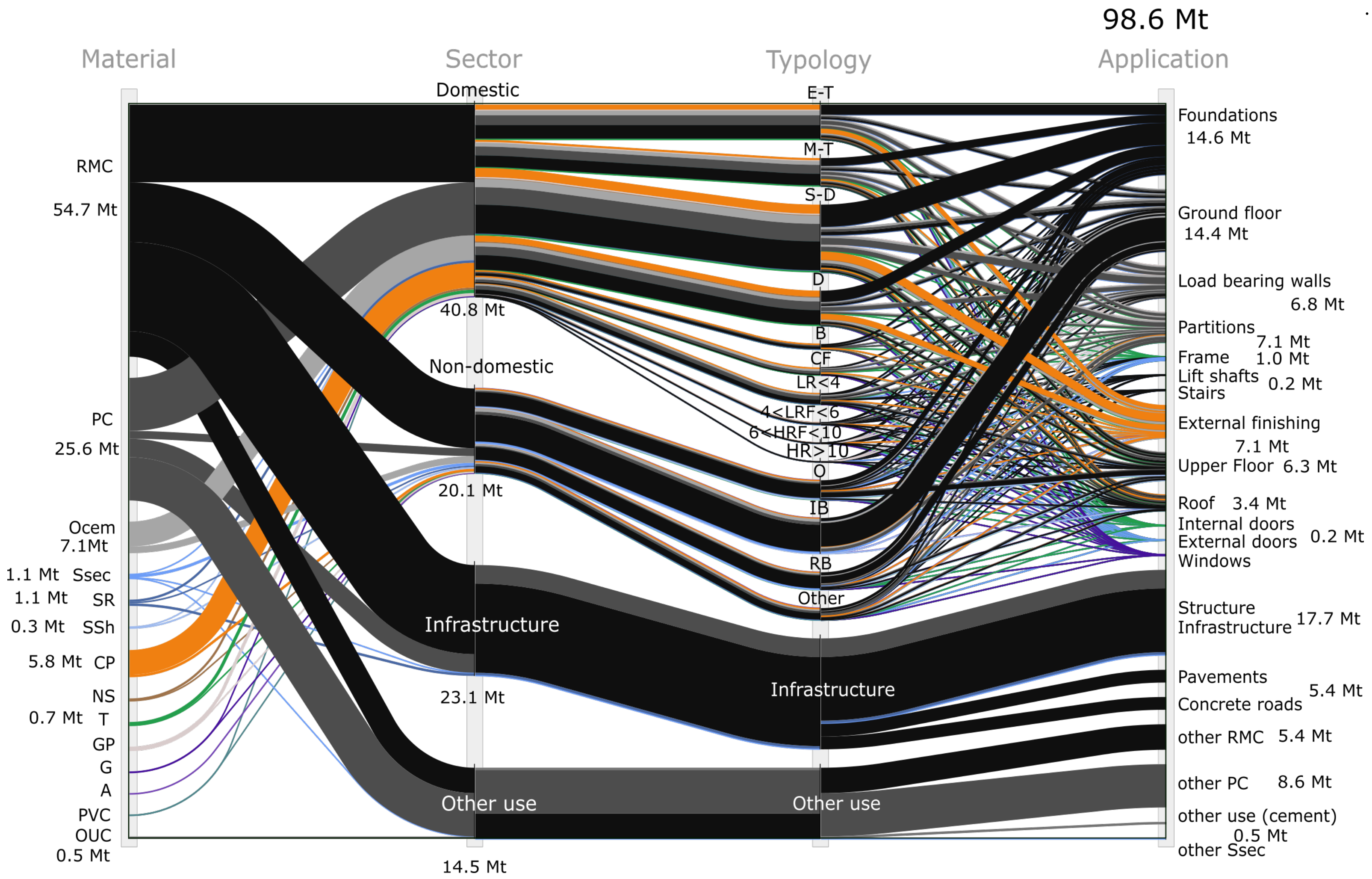

Figure 10: Material use in the UK construction in 2018 by material, sector, typologies and end-use, with selected volumes.
RMC - Ready-mix concrete; PC - Precast concrete (incl. reinforced and unreinforced); Ocem - Other cementitious (incl. mortar, plaster, screed); Ssec - Steel sections (incl. hot, cold rolled, fabricated); SR - Steel reinforcement; SSh - Steel sheet (incl. steel deck, cladding); T - Timber; CP - Clay products (incl. bricks and tiles); NS - Natural stone (blocks, tiles); GP - Gypsum products; G - Glass; A - Aluminium (incl. sections, cladding); PVC - PVC (used for windows and doors), OUC - other use of cement.

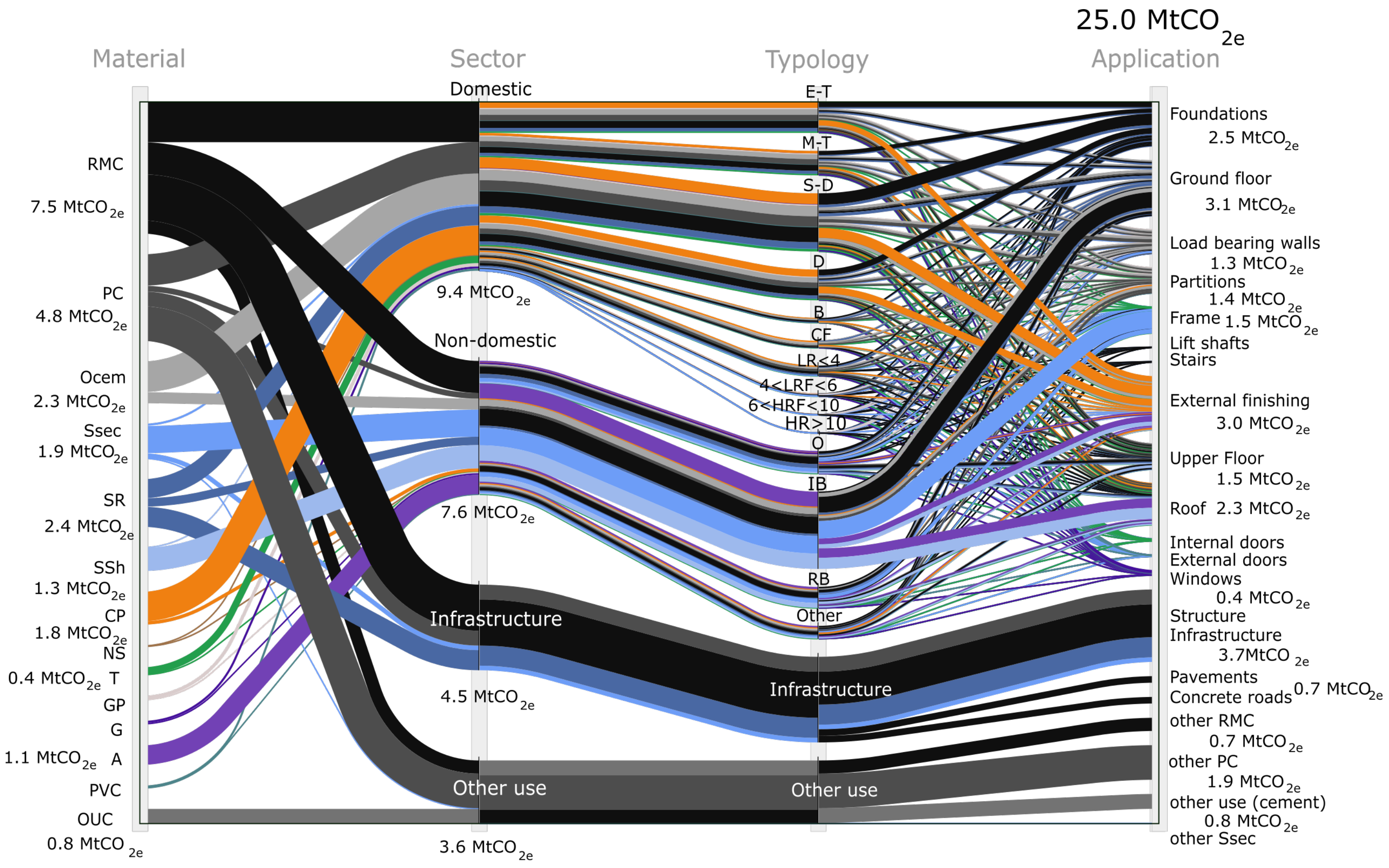

Figure 11: Updfront embodied carbon in the UK construction in 2018 by material, sector, typologies and end-use, with selected volumes.
RMC - Ready-mix concrete; PC - Precast concrete (incl. reinforced and unreinforced); Ocem - Other cementitious (incl. mortar, plaster, screed); Ssec - Steel sections (incl. hot, cold rolled, fabricated); SR - Steel reinforcement; SSh - Steel sheet (incl. steel deck, cladding); T - Timber; CP - Clay products (incl. bricks and tiles); NS - Natural stone (blocks, tiles); GP - Gypsum products; G - Glass; A - Aluminium (incl. sections, cladding); PVC - PVC (used for windows and doors), OUC - other use of cement.

5. Discussion

5.1. Comparison of bottom-up and top-down analyses

This study presents a bottom-up analysis of material use and embodied carbon in UK construction for 2018, based on a detailed model of typical building typologies and construction technologies, with some generalisations made for the more diverse non-domestic retail and other sectors. Trade statistics were used for the more complex infrastructure sector and other uses.

This section compares the results with previously published top-down analyses. Cement and concrete consumption was found to be a similar level to that reported by MPA [42] and ERMCO for 2018 [39] (RMC - 54.0 Mt [39] vs 54.7 Mt in this study, cement 11.7 Mt [42] vs 11.5 Mt in this study). However, the estimated steel consumption (rolled sections, fabricated sections, hollow sections, light sections) was 20% higher than that reported by BCSA [38] (0.9 Mt [38] vs 1.1 Mt in this study), and for steel reiforcement 18% higher than that provided in communication by TCC [44] (0.9Mt[44] vs 1.1 Mt in this study). Apart from communication with TCC, no official statistics were found except the LIBERTY UK news saying "UK market demand for reinforcement bar (rebar) amounts to c.1.2 million tonnes annually (...)" [102]. This gives high confidence about the results. Structural timber consumption was close to calculated in Section 2.1 (0.53 Mt vs 0.48 Mt in this study).

There are several underlying reasons for the difference noted with top-down approaches. The UK GBC use a multi-region input-output model to estimate an embodied carbon of 43 $MtCO_{2e}$ for UK construction in 2018 [3]. This includes all materials used in this sector as well as the distribution of people and products, design and other unspecified activities. In their analysis, material extraction, manufacturing and production, on-site construction activities as well as distribution of products gives 36.5 $MtCO_{2e}$. Almost 26.2 $MtCO_{2e}$ is connected to materials such as Cement&Concrete, Timber, Plastic&Chemicals, Steel&Other Metals, Bricks&Ceramic and Glass.

The equivalent figure for the analysis in this study is 25.0 CO_{2e}, which includes the materials listed above and natural stone, gipsum products (for wall finishing) and aluminium (cladding, doors, windows) but only for new construction. In this study only Cement&Concrete as well as constructional steelworks was analysed for all construction. Table 9 compares the UK GBC top-down analysis and the bottom-up approach used here. Materials with the same boundaries are Cement&Concrete, Steel (and other metals) and Bricks (and ceramic). In this first case, the top-down analysis was approximately 15% lower. Differences could be due to differences in embodied carbon coefficients - as shown above the total amount of concrete and cement matches with trade statistics. For steel the difference was 125%. No detailed information was found on what the UK GBC "Steel&Other Metals" category include. In this study we have included steel sections (hot and cold rolled, fabricated sections, light sections and hollow sections - constructional steelworks), steel reinforcement and steel sheet (only for new construction). According to official statistics

0.9 Mt constructional steelworks BCSA [38] was used in 2018 and 0.9 Mt of steel reinforcement [44]. If we only consider constructional steelworks and steel reinforcement and use typical for the UK carbon coefficients from [4] with 59% recycle content (cradle-to-gate, steel sections 1.53 kgCO$_{2e}$/kg, steel reinforcement 1.40 kgCO$_{2e}$/kg) we will get approximately 2.64 MtCO$_{2e}$, so similar value to the UK GBC estimations. This calculated value only relates to cradle-to-gate, so approximately 95% of upfront embodied carbon. Also does not include all other steel and metals that could have been used in 2018 in construction. This makes that the UK GBC results might be underestimated. In this study, if rather than using carbon coefficients included in ICE 3.0 [76] (100:0 method - recycled content method with lower recycling content, global average), we used UK typical values from ICE 2.0 from 2011 [4], we would get 3.22 MtCO$_{2e}$, 20% higher than UK GBC - only for constructional steelworks and steel reinforcement.

Similar to bricks and ceramics. For this category, UK GBC found 1.3 MtCO$_{2e}$. Total consumption of bricks alone in 2018 was approximately 5.5 Mt [40]. Upfront carbon emissions from bricks should vary between 1.7 MtCO$_{2e}$ (this study) up to 2.24 MtCO$_{2e}$ (carbon coefficients from ICE 3.0 [76]). In this study we have estimated consumption of clay bricks alone in new buildings 5.2 Mt with upfront carbon 1.64 MtCO$_{2e}$. It is highly possible that the UK GBC model underestimates this category as well.

Table 9: Comparison of UK GBC (top-down) analysis and this study (bottom-up) - materials

Material	UK GBC [3] MtCO$_{2e}$	This study MtCO$_{2e}$
Cement and Concrete	13.3	15.4[a]
Timber	4.7	0.4[b]
Plastic and Chemicals	3.0	0.1[c]
Steel and other metals	2.6	5.9[d] (4.6[e])
Bricks and Ceramic	1.3	1.8
Glass	1.3	0.2[f]
Sum	26.2	23.8

[a] for all construction
[b] Timber only for structural purposes for new buildings
[c] PVC only for windows and doors for new buildings
[d] constructional steelworks (hot and cold rolled sections, light, fabricated, hollow sections), steel reinforcement, steel sheet
[d] excl. steel sheet
[f] only for new buildings

Both a bottom-up and top-down analysis are sensitive to input data and therefore uncertain. Nevertheless, detailed bottom-up mapping of materials and upfront embodied carbon, even if time consuming, give an overview on where can we focus our efforts to reduce the environmental impact of construction. This analysis shows that the distribution of carbon is spread among many different components and typologies within domestic and non-domestic buildings. Less variety of materials is seen in ‘Infrastructure’ and ‘Other use’ (refurbishment, repairs, extensions and maintenance), which are dominated by concrete, cement and steel (steel reinforcement ans steel sections). It is clear that domestic buildings are dominated by concrete, other cementitious materials (mortar, screed, render) and clay products, whereas in non-domestic buildings steel

(steel sections, sheet and reinforcing bars) and concrete are predominant. In both cases concrete is mainly used in foundations and ground floor slabs.

5.2. *Decarbonisation strategies for cement and concrete*

Concrete and cementitious materials are hard to decarbonise because around 50–60% of their production emissions are from the chemical decomposition of the raw materials [103]. This means that emissions reductions techniques, such as alternative fuels and energy efficiency can only impact other parts of the industry's emissions, with the remainder requiring industry-specific solutions. As a result, it is crucial to minimise volume of concrete used in construction. Dunant et al. [66] established a list of design considerations that architects and structural engineers should account for when creating an initial design to lower the embodied carbon: the complexity of the layout, the optimisation of the design and the choice of the decking technology. Shanks et al. [19] identified cement and material efficiency, post-tensioning, precast, reducing cement content and use of calcination clays as a strategies to reduce almost 50% of carbon emissions from use of cement. Hibbert at al. [20], apart from concrete structural efficiency, identified short-term emissions reduction strategies, including: use of alternative materials, use pre-cast elements, use of admixtures, use of waste as fuel, increase efficiency of cement production & electrification, use of local materials. Short-term strategies can bring overall savings 21% compared to an average UK mix baseline. Hibbert et al. also identified maximum potential combination with 93% savings potential. These also include technologies that are not ready yet. The maximum potential combination includes increased structural efficiency, use of calcined clays, improving existing mixes, use non-PFA/GGBS AAMs, use of energetically modified cements, biocement, hydrogen as fuel, and use of oxyfuel carbon capture. Some of these have been adopted by the authors of the LCCG's The Low Carbon Concrete Routemap [104].

Figure 6 analysed commonly use technologies in the UK for different typologies. It does not include low carbon intensive such as construction floors using vaults, timber pile foundations, timber frame with hemp insulation or other. Nevertheless, switching to already mature and well known lower carbon technologies such as timber frame light structures or one leaf external walls - clay blocks (with maintaining required thermal properties) can bring up to 40% of upfront embodied carbon savings for domestc buildings.

5.3. *Demolition and circularity*

Adaptation of circular economy principles in can have significant impact on upfront embodied carbon reduction in construction. Construction is largely not circular at present. For a typical concrete frame building, approximately 75% of concrete frame is downcycled in the end-of life. For timber framed, 60% timber is landfill [105]. Only steel has a high recycling rate [105]. Reuse of materials to deliver new buildings is crucial to lower embodied carbon in construction. Annually, approximately 26 Mt of hardcore waste is produced from demolition [55], with 60% from buildings (0.8m m^2 domestic and 13.9 m^2 non-domestic).

As a result, the total annual carbon savings by completely avoiding demolition is up to 7 $MtCO_{2e}$, of 30% of the total calculated here.

5.4. Typology

During the COVID-19 pandemic, most office buildings were empty due to the stitch to living and working from home, and this trend continues even as restrictions are lifted. Currently we have approximately 660m m^2 of non-domestic buildings in the UK [31], of which a fifth are offices. In this study we have found that conversion and change of use from office, agricultural, storage and light industrial is the least carbon intensive means of creating new residential units. Converting half of office space to domestic purposes can cover approximately two years of current living space demand and bring approximately 10 $MtCO_{2e}$ in emission savings. In cities such as London, already a half of new construction projects are refurbishments, but this represents only 0.12m m^2 [67].

In this study we found that upfront carbon for detached and bungalows is is higher and mid-terraced houses is lower than other typologies, although end-terraces are appreciably higher. Carbon savings can therefore be achieved by building longer rows of terraced houses with a greater proportion of mid-terraces.

We have found also that with increasing the height of residential buildings, the upfront carbon decreases. In an extreme case, if in 2018 all new living floor space was built as HRF>10, the savings would have been 1.7 $MtCO_{2e}$.

5.5. Vacant and second homes

There were 634,000 vacant dwellings in England in 2018[2]. For the UK, we can therefore expect approximately 750,000 and 69m m^2. In 2018 approximately 292,000 dwellings were competed (new domestic buildings as well as flats converted from non-domestic buildings [30]), with an overall floor area of 25.8m m^2 and average upfront embodied carbon of 366 $kgCO_{2e}/m^2$. The UK Government plans to deliver 300,000 new homes a year by the mid-2020s in England [106], giving 350,000 in the UK. Occupying all vacant buildings we can therefore cover 2-2.5 years domestic buildings demand and save almost 20 $MtCO_{2e}$ of upfront carbon.

In 2018, there were approximately 588,000 second homes in the UK, based on 495,000 in England [30]). Based on a similar approach to the above, using these homes for permanent use could cover an additional 2 years of demand and with 20 Mt CO_{2e} of upfront carbon savings.

5.6. Next steps

This study does not cover the impact of refurbishment and maintenance, only conversion. Nevertheless, the overall use of concrete and steel in ‘Other use’ can be assigned for this purpose. We have estimated

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[2] long-term empty homes which have been unoccupied and substantially unfurnished for over six months, as well as dwellings undergoing major structural repairs for up to 12 months

that approximately 15% - 20% of total upfront embodied carbon can be assigned to refurbishment, repairs, extensions and maintenance. A detailed analysis of this is a next step of this study, as is the development of a detailed bottom-up model for infrastructure in the UK.

6. Conclusions

This paper presents the first estimate of the material consumption and embodied carbon of UK construction based on a bottom-up approach.

The analysis is a 'starting point' for seeking embodied carbon reduction and focusing the industry's efforts to achieve sustainability. Mapping of materials, even if time consuming, gives the opportunity to find hot spots where the greatest savings can be made. Effective strategies include shifting the proportion of domestic typologies form detached to terraced houses and high-rise flats, increasing conversions from non-domestic buildings, and improving structural efficiency, and prioritising lower-carbon construction technologies, especially for foundations and ground floors which account for one fifth upfront embodied carbon. Cementitious materials were found to make up 66% of all embodied emissions.

There are many small interventions which can reduce upfront embodied carbon. They are distributed throughout the construction supply chain and therefore all sectors must take the action towards embodied carbon reduction. The first step should be always, build 'only where necessary', then to 'design using minimum materials' and with 'low carbon materials'. Switching to the lowest carbon technology is crucial. To deliver this, a greater understanding of carbon vs circular economy is essential and therefore education is crucial. To achieve the greatest savings, the construction industry must to accelerate the use of already available technologies which are more carbon-efficient. In the building sector, embodied carbon savings by avoiding demolition, using vacant domestic buildings and second homes, and converting office buildings into residential, can reach up to 60Mt CO_{2e} - four years of the total 2018 carbon cost.

7. Supplementary information

Supplementary Information for this study is available from the University of Leeds at https://doi.org/10.5518/1176.

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