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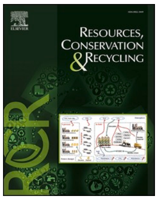

Full length article

Mapping material use and embodied carbon in UK construction

Michał P. Drewniok [a,*], José Manuel Cruz Azevedo [c], Cyrille F. Dunant [c], Julian M. 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, UK
[b] Department of Architecture and Civil Engineering, University of Bath, Bath, UK
[c] Department of Engineering, University of Cambridge, Cambridge, UK

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ABSTRACT

The latest available high-level top-down analysis shows that the embodied carbon of the UK construction in 2018 was 43 $MtCO_{2e}$, of which 80% came from materials and on-site activities. In this paper, for the first time, we combine a detailed bottom-up model of representative residential and non-residential buildings with top-down infrastructure and other material consumption data to quantify the material use and embodied carbon in UK construction. We found that almost 100 Mt of materials were used with an embodied carbon of 25 Mt CO_{2e}. Half of these emissions were from concrete. We found that existing top-down approaches underestimate emissions by up to 20%. We developed a benchmark for UK building typologies and explore interventions to achieve the UK's carbon reduction goals. We found that conversion from non-domestic to domestic purposes can bring 34% embodied carbon savings of the construction total, 30% by avoiding demolition, 20% by switching to the most material and carbon efficient technology options and by 10% if all new houses were multi-storey buildings. We have shown that the bottom-up approach allows identifying areas with high potential for decarbionisation. Due to the flexibility of the model, it can be successfully used in other countries and regions.

1. Introduction

The construction and operation of buildings and infrastructure is responsible for 47% of global final energy-related CO_2 emissions. About a third is related to the manufacturing building construction materials such as steel, cement and glass (IEA, 2022). In 2019, the UK became the first major economy to commit to a net zero emissions target (The Climate Change Act, 2008). The UK built environment accounts for 25% of the UK's total greenhouse gas emissions, a quarter of which comes from new materials (Green et al., 2021). Decarbonising the built environment will require improvements in material production, energy efficiency, heating and waste production (IEA, 2022). However, these improvements will not be sufficient to meet global and UK emissions targets if resource efficiency is not concurrently improved (Allwood et al., 2019). A detailed analysis of the current use of materials (and their emissions) in construction is needed to identify the most effective areas for implementing material efficiency strategies.

Apart from global, regional and national material statistics, there is no detailed information on the use of materials in construction. This also applies to the UK, although some studies focus on material stocks rather than construction. Tanikawa and Hashimoto (2009) analysed the material stock in buildings in Salford Quays, Manchester, UK, from 1849 to 2004, finding a stock of approximately 3.1 Mt in 2004, with aggregates, concrete and bricks each accounting for 20%. The rest was mortar, steel, wood and other materials. Streeck et al. (2020) used dynamic material flow analysis (DMFA) to assess the total material stock in the UK as 18±0.7 Gt with an annual increase of 1% per year. They found that approximately 370 Mt of materials are used annually in the construction sector, 60% of which are aggregates, 22% concrete, 10% asphalt, 4% iron and steel. This study did not trace the end of use of the materials, however. For timber, Romero Perez de Tudela et al. (2020) used a bottom-up approach to quantify stocks in existing buildings in the London Borough of Tower Hamlets, finding a timber intensity of 20–34 kg per m^2 of floorspace in terraced houses and 5.4–11 kg/m^2 for flats and maisonettes.

Existing work on material use in UK construction is limited to specific material types or regions, and usually are pre-2014. Studies on the use of steel concluded that consumption in the construction sector was approximately 3 Mt in 2000 and 2001 (Davis et al., 2007; Geyer et al., 2007). Ley et al. (2003) estimated that the UK steel construction sector accounted for 7.1 $MtCO_2$ emissions in 1998, with 80% from production. Some studies also exist which map UK cement consumption. Shanks et al. (2019) used Material Flow Analysis (MFA) to map cement use from

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[*] Corresponding author.

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raw materials to end use in the UK for 2014, and estimate 13 Mt of cementitious material use, with half in non-residential buildings, 35% residential buildings and 10% in infrastructure. They did not calculate total emissions from cementitious materials or provide a detailed breakdown of emissions sources, but identified strategies to reduce emissions. Hibbert et al. (2022) using bottom-up approach calculated 8.4 $MtCO_{2e}$ emissions from the UK cement sector in 2018, with almost 50% from ready-mix concrete, 33% pre-cast products and 15% builder's merchants. Domenech Aparisi et al. (2020) conducted an MFA for plastic in UK in 2016, finding that 0.6 Mt is used in construction. This is less than the 0.9 Mt for 2017 found by Drewniok et al. (2022) and Cullen et al. (2020), who used a top-down material flow analysis (MFA). Even though these studies provide a granular overview of the impact of using individual materials in the UK construction sector, they do not consider the interactions between materials which are needed to implement decarbonisation strategies.

Over the last decade, research has been carried out to characterise the material intensity and embodied carbon at the building-level. Examples include the WRAP Embodied Carbon Database (WRAP, 2017), the Embodied Carbon Benchmark Study at the University of Washington (ECBS, 2017; Simonen et al., 2017), "deQo" (database of embodied quantity outputs (De Wolf et al., 2019; Simonen et al., 2017). These calculations consider individual multi-storey residential and office buildings. However, these typologies represent only 3–5% of new builds by floor area in the UK (EHS, 2022; VOA, 2019), with the remainder being low-rise houses. The databases include non-UK specific building technologies. De Wolf et al. (2017) identified barriers to the effective measurement and reduction of embodied CO_{2e} in practice, which include uncertainties in carbon coefficients and methodologies. Existing databases of material and emissions intensity of buildings need to be expanded to include all the relevant building typologies.

Currently, only high-level estimates of UK construction emissions are available, such as the multiregion input-output top-down approach calculated on consumption-based emissions published by the UK Green Building Council (Green et al., 2021). This model quantifies emissions of the most significant construction materials (Cement&Concrete, Timber, Plastic&Chemicals, Steel&Other Metals, Bricks&Ceramic, Glass and Other - Supplementary Information (SI) (Drewniok et al., 2023), Fig. 3). Emissions are assessed at a high-level of data aggregation for the following categories: domestic buildings, non-domestic buildings and infrastructure. The top-down data shows that the total embodied carbon over the last decade from UK construction is quite constant (SI, Fig. 2).

A more granular, bottom-up analysis of the use of materials and associated embodied carbon is crucial to identify areas where required interventions should be taken to reduce carbon emissions and meet the climate targets. This paper aims to address the lack of detailed information on the use of materials and related emissions in UK construction. The modelling used for this purpose covers common building typologies and the most common technologies used in construction around the world. This allows the model to be applied in any country, taking into account regional averages or actual values of embodied carbon factors (e.g. from the Environmental Product Declarations). For the UK, the results will allow identification and prioritisation of areas with the highest material and carbon intensity in construction thus identifying the most critical areas for future decarbonisation strategies. Furthermore, it will provide detailed material and carbon breakdowns of common UK building typologies representing current UK practice, and can therefore be used for benchmarking. The bottom-up methodology can also be applied in other countries as it covers the most commonly used technologies in construction.

The objectives are as follows:

- To use a bottom-up approach to trace material consumption in buildings and a top-down for Infrastruc- ture and other uses in UK construction in 2018, including steel, aluminium, concrete, cementitious materials, timber, glass, plastic, gypsum products, PVC and stone;
- To quantify the associated upfront embodied carbon emissions that include raw material extraction, production, transportation and construction processes (cradle-to-practical completion);
- To identify areas and propose interventions to reduce the upfront embodied carbon;

The scope of this study covers all UK construction, including domestic buildings, non-domestic buildings and infrastructure. The analysis is performed for 2018, which is the most recent available high-level data available to calibrate the model (e.g. statistics on the use of main materials and top-down calculations on UK construction emissions). It is also expected that UK construction output in 2022 will be similar to 2018. Since then, the value of construction work decreased by 7% in 2020 (ONS, 2020). In 2021, construction activities rebounded back to pre-pandemic levels in most major economies (IEA, 2022). In the UK it was 1.5% lower than in 2018 (ONS, 2022a). Construction output up 3.7% in first half of 2022 compared to the same period in 2018 (ONS, 2022a). However, the second half of the year brought the recession and it is expected that total construction output will not exceed pre-pandemic level in until after 2024 (BEIS, 2022).

2. Approaches to material flow analysis

Material flow analysis (MFA) allows tracking of materials from extraction, production, consumption, recycling and disposal (Bringezu and Moriguchi, 2018). This can describe either resource flows in a single point in time or over a specific period of time including future stocks and flows - dynamic material flow analysis (DMFA) (Müller et al., 2014).

The results of a bottom-up account provide a detailed account of resource flows at a single point in time. Due to the complexity of a bottom-up approach, it is likely to be applied to smaller areas (e.g. cities), or larger ones using less detail. Müller et al. (2014) reviewed sixty DMFA studies on metals flows and stocks, with only six using a bottom-up approach. They conclude that a bottom-up approach can provide important insights on consumer behaviour that influences the product lifetime, disposal pathways, sociocultural and spatial patterns of material use. Tanikawa et al. (2015) listed 25 DMFA studies which analysed material stocks including materials used in construction, with only four using a bottom-up approach. They identify challenges of a bottom-up approach, as well as many advantages. Augiseau and Barles (2017) 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. They pointed that the development of case studies and the coupling of top-down and bottom-up approaches would improve the reliability of estimates. Augiseau and Barles (2017) similarly stated that relevant crossing of different data sources and of top-down and bottom-up approaches can also enhance the reliability of estimates.

3. Methodology

The analysis is performed for 2018, which is the most recent available high-level data available to calibrate the model. It is also expected that UK construction output in 2022 will be similar to 2018. According to the Department for Business, Energy & Industrial Strategy (BEIS), total construction output will not exceed its pre-pandemic level in 2019 until after 2024 (BEIS, 2022). Construction output up 3.7% in first half of 2022 compared to the same period in 2018 (ONS, 2022), but the second half of the year brought the recession (BEIS, 2022), making a 2018 study representative of the current market in terms of construction output. Since 2018 the structure of construction output has changed. New housing, infrastructure and industrial works increased by 7, 22 and 32%, respectively. Domestic and non-domestic repair and maintenance increased as well by 10 and 15%, respectively. At the same time non-domestic new builds decreased by 26% (ONS, 2022). Nevertheless, the use of main materials (sand and gravel, ready-mix concrete, bricks, concrete blocks, constructional steelworks) remains either on the same or slightly lower level, 2–4% compared to 2018 (BEIS, 2022; BCSA, 2021).

In this study, a bottom-up approach was used for buildings in order to obtain the highest possible data resolution. However, the diversity non-building projects (Infrastructure sector, incl. ‘Infrastructure’, ‘Roads’, ‘Pavements’) as well as external works, refurbishment, repairs, extensions and maintenance (‘Other use’) makes the use of a bottom-up approach problematic, so a top-down approach was used in these cases.

Fig. 1 summarises the approach used for each construction category.

The total material used in 2018 in UK construction was calculated according to Eq. (1):

$$M_{UKC} = \left(M_{m(i)} + M_{w(m)}\right) \times A_n \times FA_{(i)} + M_{m(I)} + M_{m(O)} \tag{1}$$

where:

M_{UKC} - materials used in 2018 in UK construction,

$M_{m(i)}$ - m material intensity per m^2 per i building typology,

$M_{w(m)}$ - material wastage from m,

A_n - share of the technology to deliver new projects (e.g. share of domestic buildings using cavity walls or timber frame, etc.),

$FA_{(i)}$ - overall floor area of i typology,

$M_{m(I)}$ - m material used in Infrastructure sector (‘Infrastructure’, ‘Pavements’ and ‘Roads’),

$M_{m(O)}$ - m material used for ‘Other Use’.

3.1. Buildings

The bottom-up analysis includes ten domestic building typologies (listed on Fig. 1 and included in SI, Section 3) and five non-domestic building typologies (Fig. 1 and SI, Section 4). The material intensity per m^2 for each building typology was established by adopting representative case studies. The scope has been limited to the ‘shell and core’, which includes the superstructure, substructure, façade, doors, windows, partition walls and ceiling finishes (SI, Figure 10). Each building typology was designed using multiple common UK technologies for its various components, with their proportions determined from interviews with industry professionals. In terms of materials, the study includes cement, steel sections (hot rolled), fabricated sections (from steel sheet), steel reinforcing bars (rebars), cold rolled steel sections (made from steel sheet), steel sheets (steel deck), aluminium sections (extruded aluminium), aluminium sheets, structural timber, clay products, glass, stone products, gypsum plaster, plasterboard, PVC and glass. Once the material intensities per m^2 were found, they were then scaled up to the annual domestic buildings deliveries reported in the English Housing Survey (EHS) (EHS, 2022) (Eq. (1)).

No data is available on annual non-domestic building construction, only net additions are available from the Valuation Office Agency (VOA, 2019) for ‘Office buildings’, ‘Retail’, ‘Industrial’ and ‘Other’. This does not account for demolitions. According to this data, between 2017 and 2018 net-additions of non-domestic stock 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. To find the annual construction of non-domestic buildings, the hardcore waste data arising from demolition obtained from the National Federation of Demolition Contractors (NFDC) (NFDC, 2019) was used. The downstream hardcore waste data was compared with the calculated amount of materials contained in domestic and non-domestic buildings that could be identified as hardcore waste at the end of the life of the buildings, including ready-mix and precast concrete, concrete and clay blocks, bricks, mortar, render, screed, roof tiles, concrete cladding and natural stone blocks. They represent approx. 90% of calculated weight per m^2 for low-rise domestic buildings and non-domestic buildings, and 70–85% for high-rise domestic buildings. Detailed calculations are included in SI, Section 5. This approach is a simplification, but is

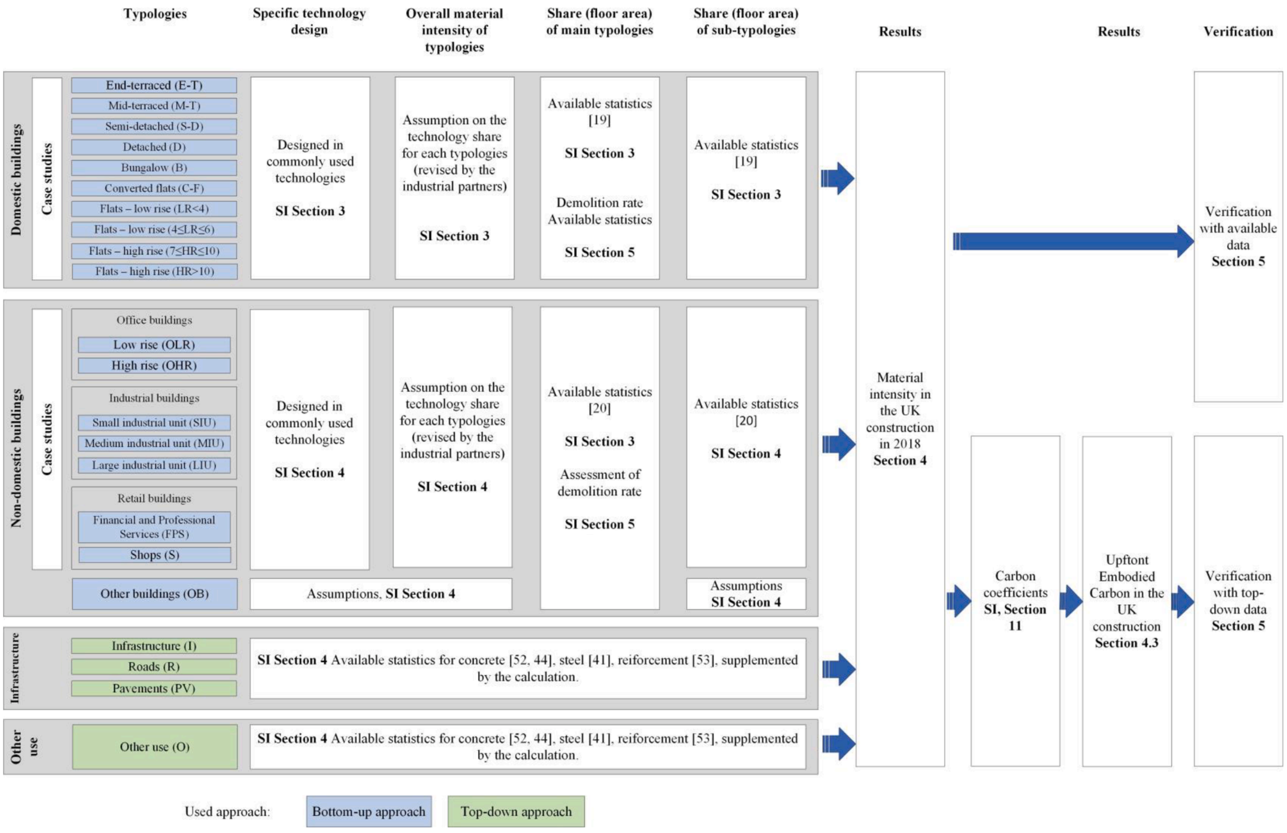

Fig. 1. Processes used to find material use and embodied carbon of the UK construction in 2018.

successfully used by others to quantify the material consumption e.g. plastic products by PlasticsEurope (Plastic Europe, 2019). The calculated annual non-domestic buildings deliveries for 2018 was used to calculate the materials used in the UK construction (Eq. (1)).

Each material intensity per m^2 also includes material wastage on-site, with specific wastage rates per material as detailed in SI, Section 10.

3.2. *Infrastructure and other*

A top-down analysis was used for Infrastructure sector (incl. 'Infrastructure', 'Pavements' and 'Roads') and 'Other use' (incl. external works, refurbishment, repairs, extensions and maintenance). This was focused on the main structural materials such as ready-mix (RMC) and precast concrete (PC), steel reinforcement (SR), steel sections (Ssec, constructional steelwork) and cement. BCSA (BSCA, 2021) reported the use of constructional steelworks for 'Infrastructure' as 160 kt and 'Other use' incl. agriculture as 27 kt. The ERMCO (ERMCO, 2019) reported that 13.5 Mt of RMC was used in 'Infrastructure', 2.7 Mt in 'Pavements', 2.7 Mt in 'Concrete roads', and 5.4 Mt for 'Other use'. To find the volume of PC used in 'Infrastructure' and 'Other use', all calculated PC elements used for new domestic and non-domestic buildings (concrete blocks, tiles, concrete facade and precast floor systems) have been subtracted from total PC volume reported by ERMCO (14.5 Mt - 2.9 Mt = 12.3 Mt). The volume of reinforcement for RMC and PC was assumed according to Table 20 included in SI.

The 'Other use' of cement was taken as 0.5 Mt from (MPA, 2020). On-site waste was not included in the top-down analysis as reported values are estimated based on purchased quantities. All calculations are detailed in SI, Section 4.5.

3.3. *Embodied carbon*

For UK material used in construction, carbon coefficients for each materials were found from available data sources (SI, Section 12, Table 32) and multiplied by the material volume (Eq. (2)). Analysis in this study covers materials and construction processes up to practical completion (Modules A1-A5 (BS EN, 2010; Anderson et al., 2021), 'upfront embodied carbon' (Anderson et al., 2021)). 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) (Orr and Gibbons, 2022). 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.

It is uncertain how and where construction materials and products are produced, so the Inventory of Carbon and Energy (ICE), V3.0 BETA (ICE) was taken as the main source for carbon coefficients (Modules A1-A3). As a result, they represent world averages. If materials were not listed in the ICE (ICE), carbon coefficients for Modules A1-A3 were found 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 $gCO_2eq/kg/km$ (BEIS, 2021) (SI, Table 31). Emissions related to construction processes (Module A5) include those from material wastage, plus the transportation of waste away from site. Material-specific wastage rates are included in the SI, Section 10, Table 31. For all materials, waste transportation was assumed as 5 $kgCO_2eq/t$ (the default assumption from (RICS Professional Guidance, 2014)). Processing and disposal of construction waste was assumed as 1.3 $kgCO_2eq/t$ (Orr and Gibbons, 2022).

$$C_{UKC} = C_m \times \left[\left(M_{m(i)} + Mw_{(m)}\right) \times A_n \times FA_{(i)}\right) + M_{m(I)} + M_{m(O)}\right] \tag{2}$$

where:

C_{UKC} - upfront embodied carbon cost in 2018 in UK construction,
C_m - carbon coefficients for m material.

4. Results

4.1. *Embodied carbon ranges for each building typology*

Fig. 2 presents a range of upfront embodied carbon for each typology, arising for the various technology options. All assumptions are included in SI, Tables 27 and 28, with detailed results in SI, Table 29. Fig. 2 also includes the weighted average embodied carbon values, assumed to represent current UK practice, which are carried forward into the main analysis model.

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 2) followed by precast flat panels (I), then cavity walls with concrete blocks (IV). The lowest carbon technologies were timber frames (VI) and single leaf wall with clay blocks (VIII), having approximately 55% and 35% carbon savings respectively compared to cavity walls with concrete blocks (IV).

For low rise offices (OLR), the highest embodied carbon technology was reinforced concrete flat slabs with in-situ columns (IIIa), at 600 $kgCO_2e/m^2$, with an 80% share from reinforced concrete. The lowest was Steel Composite UB Restricted Depth (IIb), at 406 $kgCO_2e/m^2$, with a third of embodied carbon from reinforced concrete and 27% from steel sections. The Steel frame and precast concrete slab (IIa) option was 10% more carbon intensive than IIb (440 $kgCO_2e/m^2$), and in-situ concrete frame with post tensioned slab (IVa) 20% compared to IIb (480 $kgCO_2e/m^2$).

For high rise office buildings (OHR), the most carbon-intensive technology was PT Band Beam and Slab (IIIb), at 525 $kgCO_2e/m^2$, with 2/3 share from reinforced concrete. The lowest was Steel Composite Cellular Plate Girders (Ib), at 393 $kgCO_2e/m^2$. Steel Composite UB Restricted Depth (IIb) was in the middle, with an embodied carbon of 487 $kgCO_2e/m^2$.

The embodied carbon for the industrial buildings SIU, MIU and LIU was 411, 435 and 410 $kgCO_2e/m^2$ respectively, giving 418 $kgCO_2e/m^2$ as a weighted average. For retail (RB) and Other (OB), the range of embodied carbon was between 350 and 467 and 300–717 $kgCO_2e/m^2$ respectively.

4.2. *Mass and embodied carbon intensity by component*

Fig. 3 shows the weighted average upfront embodied carbon for each building typology broken down by component and material. Similar results by weight are included in the SI, Figure 13.

Converted flats (C-F) are, by far, the least carbon intensive form of domestic building, followed by the tallest high-rise (HRF>10) and M-T. The most carbon intensive are bungalows (B), followed by detached houses (D). One quarter of the embodied carbon in E-T, M-T, S-D, D is in foundations, increasing to 30% for bungalows. With the ground floor included, the share is between 34 and 40% for E-T, M-T, S-D, D and reaches 52% for B. For multi-family residential buildings the foundation carbon share decreases with height from 12% for LRF<4 to 5% for HRF>10, or from 20% to 7% per m^2 with ground floor slabs included.

For E-T, M-T, S-D, D, B, the share of walls in embodied carbon is between 23 and 26% for M-T and B, 33–40% for E-T, S-D and LRF<4. The share of walls and frame (with external finishing) is the highest for bungalows at 45%. For multi-family residential buildings of more than 6 floors, it remains on a similar level at 41–43%. Upper floors are only 7–10% for E-T, M-T, S-D and D, but increase to 21–28% for multi-family residential buildings (the share increases with height).

In terms of materials, approximately 60% of embodied carbon in E-T,

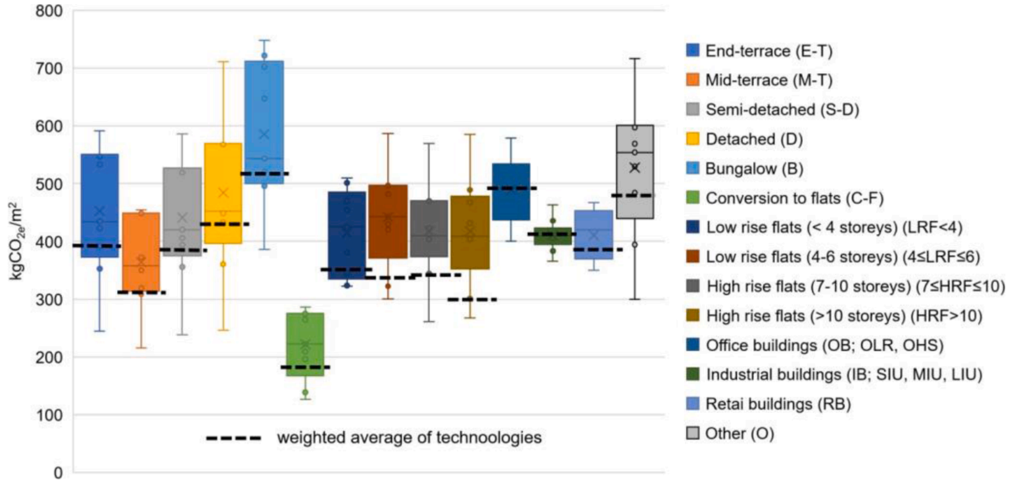

Fig. 2. Distribution of embodied carbon for each typology, based on different technologies, and the weighted average representing UK practice. See SI, Tables 27 and 28 for detailed assumptions.

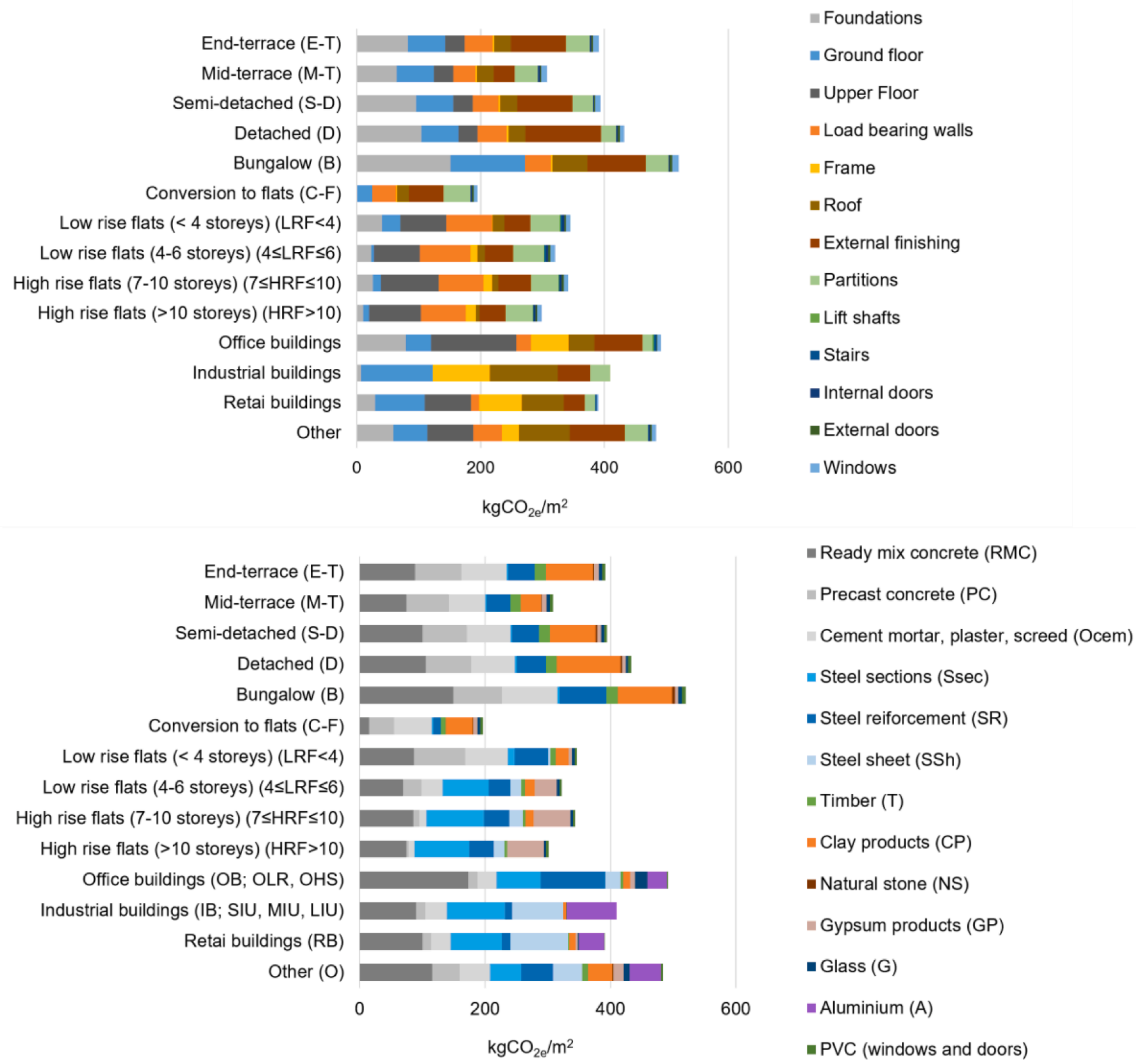

Fig. 3. Upfront embodied carbon intensity: (top) by building component; (bottom) by material type.

M-T, S-D, D, B, CF and 70% for LRF<4 is from cementitious materials. For residential buildings higher than four storeys, the share of cementitious materials decreases to 40–30%. Finishing of external walls (the external brick layer alone) in E-T, S-D, D, B is approximately 20% of upfront embodied carbon. The embodied carbon from steel reinforcement for all domestic building typologies except converted flats varied from 11 to 15%.

For HR, O, IB, and RB, approximately one third of upfront embodied carbon is from cementitious materials, almost all of which (90–95%) is from ready mix or precast concrete. The embodied carbon from steel reinforcement varied from 4% for IB and RB, to 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%.

4.3. *Material use and embodied carbon in UK construction*

The total material mass and upfront carbon emissions in UK construction for 2018 are shown in Fig. 4 and Fig. 5, respectively. In total, 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 floors, with 28% in infrastructure and 20% in non-domestic buildings, mainly for foundations and ground floors. Three quarter of all other cementitious materials, as well as 90% of clay products, were used in domestic buildings.

In terms of embodied carbon, almost 37% was from new domestic buildings, followed by non-domestic buildings at 30%. One fifth of all 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, half of the upfront embodied carbon was concrete (RMC and PC), 24% is steel, including steel sections, steel reinforcement and steel sheets. The share of other cementitious materials and clay products was 9% and 7% respectively.

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

5.1. *Use of materials*

The calculated consumption of cement and concrete was at a similar level to that reported by MPA (MPA) and ERMCO for 2018 (ERMCO, 2019) (SI, Table 33). For RMC this was 54.7 Mt in this study compared to 54.0 Mt (ERMCO, 2019), and for cement 11.5 Mt in this study compared to 11.7 Mt (MPA, 2021). However, the estimated steel consumption was 20% higher in this study (1.1 Mt) than that reported by BCSA (0.9 Mt) (BSCA, 2021), and for steel reinforcement 18% higher (1.1 Mt) than that provided in communication by TCC (0.9 Mt) (TCC). No official statistics on the consumption of steel reinforcement were found except the LIBERTY UK news saying that the “UK market demand for reinforcement bar (rebar) amounts to c.1.2 m tonnes annually (…)” (LIBERTY, 2021). This gives high confidence about the results. Structural timber consumption (0.48 Mt) was close to that calculated in SI, Section 1, (0.53 Mt) from (Moore, 2015).

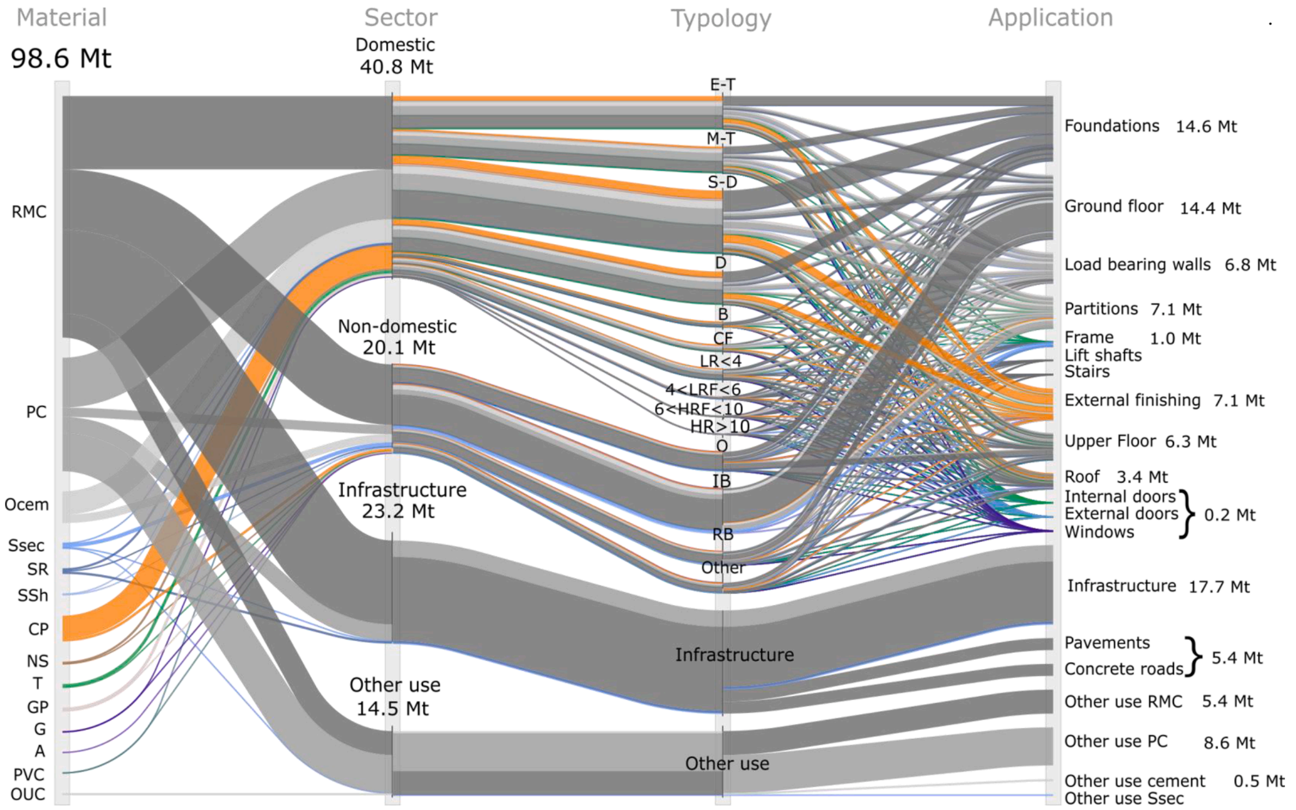

Fig. 4. Material use in the UK construction in 2018 by material, sector, typologies and end-use, with selected volumes. RMC - Ready-mix concrete; PC - Precast concrete (incl. reinforced and unreinforced); Ocem - Other cementitious (incl. mortar, plaster, screed); Ssec - Steel sections (incl. hot, cold 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. Typology - see Fig. 3. Results for materials [Mt]: RMC - 54.7, PC - 25.6, Ocem - 7.1, Ssec - 1.1, SR - 1.1, SSh - 0.3, CP - 5.8, T - 0.7, OUC - 0.5.

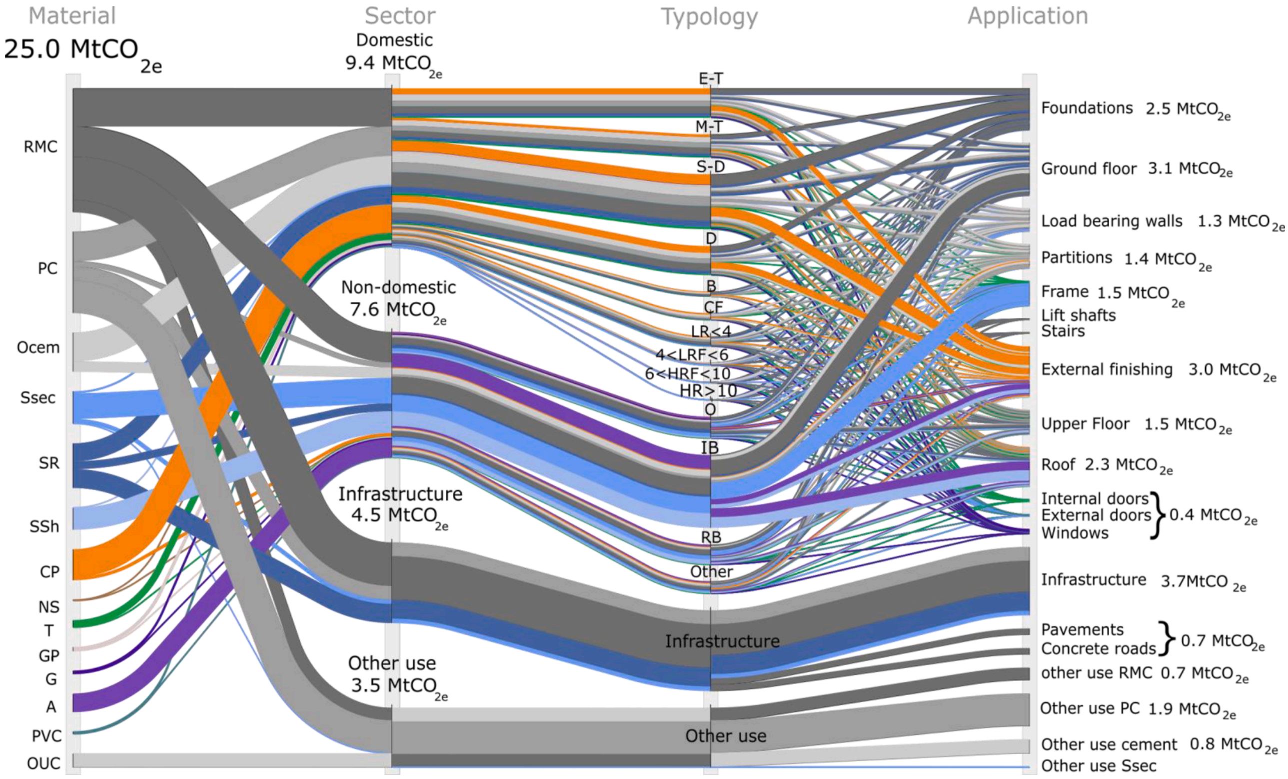

Fig. 5. Upfront embodied carbon in the UK construction in 2018 by material, sector, typologies and end-use, with selected volumes. RMC - Ready-mix concrete; PC - Precast concrete (incl. reinforced and unreinforced); Ocem - Other cementitious (incl. mortar, plaster, screed); Ssec - Steel sections (incl. 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. Typology - see Fig. 3. Results for materials [MtCO$_{2e}$]: RMC - 7.5, PC - 4.8, Ocem - 2.3, Ssec - 1.9, SR - 2.4, SSh - 1.2, CP - 1.8, T - 0.4, A - 1.1, OUC - 0.8.

5.2. *Upfront embodied carbon*

There are several possible underlying reasons for differences between bottom-up and top-down ap- proaches. The UKGBC estimated 43 MtCO$_{2e}$ (Green et al., 2021) for all materials, construction processes, distributions of people and products and design and other activities in UK construction for 2018. In their analysis, cradle-to-practical completion (Modules A1-A5) gives 36.5 MtCO$_{2e}$. Almost 26.2 MtCO$_{2e}$ is from materials such as Cement&Concrete, Timber, Plastic&Chemicals, Steel&Other Metals, Bricks&Ceramic and Glass.

The bottom-up equivalent figure (from this study) that includes new construction and other use is 25.0 CO$_{2e}$. Table 1 compares the UKGBC top-down analysis and the bottom-up approach by material. 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, possibly caused by differences in embodied carbon coefficients.

Table 1
Comparison of UKGBC (top-down) analysis and this study (bottom-up) - materials.

Material	UKGBC (Green et al., 2021) 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.
[e] excl. steel sheet.
[f] Only for new buildings.

For steel, this study calculated an embodied carbon 125% greater than the UKGBC (Table 1). No detailed information was found on the UKGBC "Steel&Other Metals" end-use. Such a significant difference may be also related to the embodied carbon factors used. In this study we have included steel sections (hot and cold rolled, fabricated sections, light sections and hollow sections), steel reinforcement and steel sheet (only for new construction) separately. Considering only constructional steelworks and steel reinforcement and the use typical for the UK cradle-to-gate embodied carbon coefficients from (Hammond and Jones, 2011) (59% recycle content; steel sections 1.53 kgCO$_{2e}$/kg, steel reinforcement 1.40 kgCO$_{2e}$/kg) we get approximately 2.64 MtCO$_{2e}$, a similar value to the UKGBC estimations. This calculated value does not include transportation and construction processes (approximately 5%). Also, it does not include all other steel and metals that could have been used in 2018 in construction. This means that the results of the UKGBC are likely underestimated. If, rather than using carbon coefficients included in ICE 3.0 from 2019 (ICE, 2019) (100:0 method - recycled content method with lower recycling content, global average) for constructional steelworks and steel reinforcement **only** we have used UK typical values from ICE 2.0 from 2011 (Hammond and Jones, 2011) we would have got 3.22 MtCO$_{2e}$, a 20% higher value than UKGBC.

A similar comparison can be made for bricks and ceramics. For this category, the UKGBC reported 1.3 MtCO$_{2e}$. The top-down total consumption of bricks in 2018 was approximately 5.5 Mt (BEIS, 2022). Based on this, the upfront carbon emissions from bricks should vary between 1.7 MtCO$_{2e}$ (this study) up to 2.24 MtCO$_{2e}$ (using carbon coefficients from ICE 3.0 (ICE, 2019)). In this study we have estimated consumption of clay bricks alone in new buildings 5.2 Mt with upfront carbon 1.64 $MtCO_{2e}$. This indicates that the UKGBC results are likely to be an underestimate.

6. Discussion and evaluation of carbon reduction interventions

Detailed analysis of the use of materials in construction allowed identification of the areas where we can minimise their environmental impact. This analysis focuses on the UK construction, but as the model covers common building typologies and the most common building technologies can be used in any country.

6.1. Material decarbonisation

The distribution of carbon is spread amongst many different components and typologies within domestic and non-domestic buildings. However, in terms of materials, it is clear that concrete and other cementitious materials are dominant, accounting for two-thirds of embodied carbon compared to 22% from steel and 7% from clay products.

Based on literature, decarbonisation rates by 2050 varies for different materials, e.g. 36% for cementitious materials, 36% for steel, 76% for aluminium, 47% for timber, 31% for PVC (Drewniok et al., 2023). They include electrification, material and energy efficiency in production, fuel change, but exclude Carbon Capture and Storage (CCS) technologies and the use of hydrogen as being unlikely, due to their current lack of development at significant scale.

Decarbonisation of cementitious materials is difficult since around 50–60% of the embodied carbon from cement production is from the chemical decomposition of the raw materials (Van den Heede and De Belie, 2012). The subject is, however, of much research and analysis. Shanks et al. (2019) propose an upper limit of 50% emissions reduction in the UK, though material efficiency, post-tensioning, precast, reducing cement content and use of calcination clays as Supplementary Cementitious Materials (SCMs). Currently, the most common intervention to reduce the embodied carbon of cement and concrete is the use of Ground Granulated Blast Furnace Slag (GGBFS, by-product of iron from iron ore in blast-furnace) or Fly Ash (FA, produced at coal-fired power plants). These two SCMs are limited commodity and we do not expect to increase their availability due to carbon reduction targets - transition to secondary steel production from steel scrap in Electric Arc Furnaces (EAF) and transition to zero-emission energy production (Scrivener et al., 2018). Therefore, from the global and local perspective, the rapid development of new SCMs is necessary. This include the use of calcinated clays due to their global availability. Hibbert et al. (2022), aside from concrete structural efficiency, identified short-term emissions reduction strategies to give a 21% overall savings for UK concrete. Only with many immature technologies, such as calcined clays, use non-PFA/GGBFS AAMs, energetically modified cements, biocement, hydrogen as fuel, and oxyfuel carbon capture, was a saving close to full decarbonisation achieved. These require additional R&D projects and significant capital investments.

Steel production can be electrified, but only for scrap steel in EAF, and therefore only if scrap steel is available to cover the demand. By 2060, the share of EAF production will exceed the share of primary steel production globally. Regional availability, quality, and trade patterns of scrap will influence production route choices (Xylia et al., 2018). Currently, the share of primary steel production is 75% and 60% globally and in the EU, respectively. In the UK the share is 80% (WSA, 2019). At the same time nearly 80% of steel scrap, equivalent to 80% of UK apparent demand, is exported oversees for recycling (MakeUK, 2021). The UK's medium-term strategy to lower the embodied carbon of steel products should be to convert steel production to EAF and avoid exporting the valuable raw material used for EAF - steel scrap. This require significant capital investments and will have social costs. The short-term solution is to procure the steel from existing EAF facilities. This solution would need to include additional emissions connected to transportation of the material.

Emissions reduction techniques such as alternative fuels and resource efficiency in production, change of production routes (e.g. BOF to EAF) may only impact a part of emissions related to construction, while the rest require industry-specific solutions. It is crucial to minimise the flow of the materials in construction while meeting the necessary needs - dematerialisation in construction.

6.2. Switching to more efficient typologies

This study found a strongly negative correlation between number of storeys and embodied carbon for domestic buildings. The typologies with the highest material and carbon intensities in the UK are single family houses (bungalows), office buildings and detached houses. The lowest carbon are medium and high- rise residential buildings and mid-terrace houses. Material and carbon can therefore be saved by building longer rows of terraced houses with a greater proportion of mid-terraces.

Currently, only 2.4% of all new domestic buildings are medium and high-rise, creating an opportunity to reduce overall emissions. In an extreme case, if in 2018 all new living floor space was built as HRF>10, the savings would be 1.7 $MtCO_{2e}$. Although unrealistic as a blanket policy, the potential for embodied emission savings through localised densification is clear. This also can support more sustainable transport. More realistically, halving the share of single and two-family houses by 2050, increasing conversions by 70%, triple the number of mid-rise residential buildings and nine times the number of high-rise residential buildings can bring almost 50% embodied carbon savings in domestic building sector (Drewniok et al., 2023) (research that used developed in study model). Densification of residential properties would require legislative and social changes. Embodied carbon savings may vary depending on the country as this paper presents technologies typical for the UK, e.g. most of single and two-family houses as well as low rise residential buildings are structured using cavity walls, less common in other countries - see Section 4.

6.3. Switching to more efficient technologies and designs

Many studies show significant carbon savings from relatively radical technologies, including vaults as floor structures (Hawkins et al., 2020), timber pile foundations and timber frames with hemp insulation (Pennacchio et al., 2017). Nevertheless, this study shows that switching to already mature and well known technologies, such as timber frames or single leaf external walls, can already reduce embodied carbon by 40% for domestic buildings, without significantly affecting their architectural function (see Section 4).

If the lowest carbon technology option was applied to every building typology, maintaining today's typology share, the total emission savings would be 4.5 $MtCO_{2e}$, or almost 20% of the total. This highlights that immediate savings can be made by prioritising embodied carbon at early design stages, as also highlighted by Gauch et al. (2022) and Dunant et al. (2021), who lists decking choice as a key parameter influencing embodied carbon in building structures, alongside layout complexity and member optimisation. A simple switch away from concrete slabs to steel composite decking can save approximately 20% of the upfront embodied carbon on an average office building (Dunant et al., 2021; Hawkins et al., 2022). Switching to the most material and carbon efficient technology in domestic buildings such as timber frame or single-leaf external walls with clay blocks can save 4.5 $MtCO_{2e}$ each year, or almost 20% of the construction total. The sustainable supply of timber is limited by the annual increment of forests. Although this is increasing in the UK and Europe, supply cannot rapidly match increased demand. Currently, 70% of the 10.4 Mt sawn timber used in the UK is imported. We have estimated that approximately 10% of total sawn timber was used for construction purposes (0.5 Mt). By making better use of sawn timber, prioritising the use of timber for structural purposes, we could increase the number of timber framed buildings while reducing the overall use of timber in the UK. More detailed study on the use sawn timber is needed to understand the final use of 95% of UK sawn timber. Based on the model developed in this study, Drewniok et al. (2023) found that 25% of upfront embodied carbon savings could be achieved in the domestic sector by using framed-framed buildings in combination with structural efficiency.

6.4. Avoiding demolition and promoting conversion

The adoption of circular economy principles in construction is considered a significant carbon mitigation solution, since construction is largely not circular at present. For a typical concrete frame building, approximately 75% of concrete frame is downcycled at the end-of-life. For structural timber frames, 58% timber is landfill (BCSA, 2021). Only steel has a high recycling rate. 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 (NFDC, 2019), with 60% from buildings (0.8 m m^2 domestic and 13.8 m m^2 non-domestic). As a result, the total annual carbon savings by completely avoiding demolition is up to 7 $MtCO_{2e}$, or 30% of the total calculated here.

Conversions for flats are nearly half as carbon and material intensive than new medium and high-rise residential buildings. Over the last decade, their share in the supply of domestic buildings has been growing year by year, reaching almost 15%. During the COVID-19 pandemic, most office buildings were empty due to the switch to living and working from home, and this trend has continued even as restrictions are lifted. Currently there are approximately 660 m m^2 non-domestic buildings in the UK (VoA, 2019), of which a fifth are offices. 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. Covering the entire demand for domestic properties through the conversion of non-residential buildings bring approximately 8.4 $MtCO_{2e}$ in embodied emission savings, 34% of the construction total.

6.5. Next steps

This paper presents a feasibility study of using a bottom-up approach to find details on the use of materials in construction and related embodied carbon. Due to the flexibility of the model, the next step will be to conduct similar research for other European countries, including Poland.

This study does not cover the impact of refurbishment, maintenance external works only conversion. Nevertheless, the overall use of concrete and steel in ‘Other use’ can be assigned for this purpose - 15% of total upfront embodied carbon. The calculations do not include either mechanical, electrical and plumbing services or painting. Including these can increase the upfront carbon for different properties by 10–15% (Rodriguez et al., 2020, Hamot and Bagenal George). The development of a detailed bottom-up model covering above elements as well as infrastructure projects is the next step of this study. This will allow to build an input-output model of material and embodied carbon to 2050 and beyond.

The next steps of the authors will be also to model the demolition curve to calculate demolition flows of non-domestic buildings in the UK.

7. Conclusions

This paper presents the first estimate of material consumption and embodied carbon of UK construction based on combined bottom-up approach for buildings and top-down for infrastructure and other use, giving a detailed picture of current construction practice to enable focused efforts for future emission reductions and material savings. This approach is applicable to other countries and regions’ construction sectors as covers common building typologies and technologies in construction.

We found a total material consumption of almost 100 Mt and ‘cradle-to-practical completion’ embodied carbon of 25 $MtCO_{2e}$ to deliver ‘shell and core’ of buildings, infrastructure, external works and refurbishments. We found that existing top-down approaches for the UK construction underestimate emissions by up to 20%.

Our results suggest that successful strategies to minimise embodied carbon in UK construction would include:

- Promoting the adaptation of non-domestic buildings for housing. This can deliver over 50% upfront carbon savings compared to purpose-built single or two-family houses, and 30–40% savings compared to multi-family residential buildings. Conversion of non-residential buildings can save 34% of the construction total. Overall, avoiding demolition can bring 30% annual emissions savings.
- Switching to the most material and carbon efficient technology options for building components. Our analysis shows that even using readily available technologies in buildings (e.g. timber frames or single-leaf external walls with clay blocks) can save 4.5 $MtCO_{2e}$ each year, or almost 20% of the construction total.
- Favouring the construction of taller residential buildings (up to 10 stories) over low-rise properties, as well as reduced detachment between buildings, can offer significant reductions in material consumption and embodied carbon. In an extreme case, construction emissions from delivering domestic properties would be 10% lower if all new houses were multi-storey buildings.
- Demand reduction. Half of total construction embodied carbon is from concrete, primarily in foundations, ground floors, upper floors and load bearing walls in new buildings and infrastructure. Reducing concrete emissions through demand reduction (1), structural efficiency (2), material substitution (3), cement replacement (4), mix optimisation (5) and is essential to tackle overall emissions.

The embodied carbon is distributed throughout the construction supply chain, requiring all sectors to take action towards carbon reduction.

Credit author statement

All authors were engaged on the conceptual ideas. M.P.D. took the lead in writing the manuscript, conceptual ideas and proof outline, methodology, modelling. W.H., J.M.C.A., C.F.D., T.I. verified analytical methods, W.H., J.M.C.A., C.F.D. interpretation of the results, proof-reading of the manuscript, visualization, review & editing.

Declaration of Competing Interest

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

Data availability

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

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