A comparative embodied carbon assessment of commercial buildings

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Synopsis

This paper presents the results from a comparative embodied carbon assessment of new commercial buildings focusing particularly on different structural forms.

The assessment is based on five recently-constructed steel-framed commercial buildings and also on redesigns of those buildings in alternative structural forms. All building and structural options analysed have been independently costed.

The embodied carbon assessment was undertaken using the life cycle assessment (LCA) model CLEAR which is based on ISO standards and has been peer-reviewed by Arup.

The results presented are a subset of a more comprehensive dataset generated under the Target Zero programme. In addition to the embodied carbon results, other findings relating to operational carbon and BREEAM, which may be of interest to structural engineers, are presented.

This paper describes Target Zero and the five buildings studied; the assessment methodologies employed and presents the principal findings and conclusions.

Target Zero

Target Zero[1] is a programme of work to provide guidance on the design and construction of sustainable, low and zero carbon buildings in the UK. Five non-domestic building types have been analysed: a large distribution warehouse, an out-of-town supermarket, a secondary school, a high-rise office block and a mixed-use (office and hotel) building (Figure 1a-e and Table1).

Using recently constructed, typical buildings as benchmarks, Target Zero has investigated three specific, priority areas of sustainable construction:

- Operational carbon – how operational energy use and associated carbon emissions can be reduced by incorporating appropriate and cost-effective energy efficiency measures and low and zero carbon (LZC) technologies, and whether it is significantly influenced by alternative structural forms
- BREEAM assessments – how 'Very Good', 'Excellent' and 'Outstanding' BREEAM (2008) ratings can be achieved at lowest cost
- Embodied carbon – quantification of the embodied carbon of buildings particularly focussing on different structural forms. This paper focuses on the results from this aspect of the studies

Target Zero was undertaken by a consortium of leading organisations in the field of sustainable construction: AECOM and Cyril Sweett with steel construction expertise provided by Tata Steel Europe RD&T and the Steel Construction Institute (SCI).

Buildings

Full cost plans for each of the five buildings were developed by Cyril Sweett. Floor area and capital construction costs are also provided (Table 1).

To provide a consistent benchmark, some minor modifications were made to the real buildings to make them equivalent, in terms of operational energy performance, to the minimum requirements under Part L (2006) of the Building Regulations. The modified buildings are referred to as the Base Case buildings in this paper.

AECOM then identified two alternative viable structural options for four of the five buildings and alternative designs were developed to RIBA Work Stage D; only one viable alternative structural form was identified for the office building. These alternative structural options were then costed by Cyril Sweett. The alternative structural options and corresponding unit capital costs are shown in Table 2.

Operational carbon

Reduction of operational carbon emissions from buildings is the primary sustainable construction driver in the UK. UK Government has set an ambitious and legally binding target[2] to reduce national greenhouse gas emissions by at least 80% by 2050 with an intermediate target of a 34% reduction by 2020 (against a 1990 baseline). The operation of buildings currently accounts for nearly half of the UK's greenhouse gas emissions and therefore significant improvement in new and existing building performance is required if these targets are to be met.

Government has announced its aspiration for new non-domestic buildings to be zero carbon and in operation by 2019, and is consulting on the definition of 'zero carbon' for non-domestic buildings. As a minimum, Government has stated that the zero-carbon destination for non-domestic buildings will cover 100% of regulated† emissions, i.e. a Building Emissions Rate (BER) of zero[3]. The most recent government sponsored research into carbon compliance targets for new non-domestic buildings[4], suggests that the reduction in regulated emissions (via energy efficiency and on or near site LZC technologies) required to achieve the 2019 'zero carbon' target, is 44% to 54% (relative to Part L 2006) with the balance

† Regulated CO_2 emissions are those building emissions that are regulated under Part L of the Building Regulations. Regulated emissions include those associated with the building fabric and fixed services. Non-regulated emissions include cooking, appliances and IT equipment.

Figure 1a
Distribution warehouse, Stoke-on-Trent

Figure 1b
Supermarket, Stockton-on-Tees

Figure 1c
Secondary school, Knowsley, Merseyside

Figure 1d
Office, Central London

Figure 1e
Mixed use (hotel and office building), Manchester

achieved via the use of allowable solutions. Although no formal definition has been given for allowable solutions, current thinking[5] is that a range of on, near and off-site solutions will be permitted including smart appliances, exporting heat and investment in local and national carbon reduction schemes.

A summary of the Target Zero operational carbon results is given in Appendix 1.

The choice of frame and framing material has a very minor impact on the predicted operational carbon emissions from the buildings studied under Target Zero. This paper therefore focuses on embodied carbon, since this is the area where the structural engineer is likely to be able to exert the greatest influence during the design process.

BREEAM

BREEAM (BRE Environmental Assessment Method) is the leading and most widely used environmental assessment method for buildings. It has become the *de facto* measure of the environmental performance of UK buildings. Although currently voluntary, many publically funded/procured buildings are required to have a minimum BREEAM rating.

The choice of frame and framing material has only a very minor impact on the overall BREEAM score.

A summary of the Target Zero BREEAM results is given in Appendix 2.

Embodied carbon

As the operational energy efficiency of new buildings is improved, the relative significance of the embodied impacts of construction materials and processes increases. In recognition of this, significant attention is now being paid to the quantification and reduction of the embodied carbon impacts of buildings and construction products[6-18].

Compared to operational carbon, quantification of embodied carbon impacts of buildings is more complex and challenging. This is mainly due to different scoping and methodology assumptions, particularly which life cycle stages are included within the scope of the assessment and how these are quantified.

It is recognised that a thorough treatment of embodied carbon should consider the full life cycle of buildings including the end-of-life impacts of demolition and the reuse and recycling of demolition materials[19]. For many construction products, there is a lack of data on the impacts after they have left the factory gate. Consequently many embodied carbon assessments are currently limited to 'cradle-to-gate' studies which exclude transport to site, construction/erection impacts, maintenance, product replacement, demolition, reuse and recycling.

Embodied carbon assessment methodology

The term 'embodied carbon' refers to the lifecycle greenhouse gas emissions (expressed as carbon dioxide equivalents – CO_2e)[§] that occur during the manufacture and transport of construction materials and components, as well as the construction process itself and end-of-life aspects of the building including demolition, reuse and recycling. The embodied carbon and the in-use carbon emissions resulting from the operation of the building (operational carbon) together make up the complete lifecycle carbon footprint of the building.

The embodied carbon impact of the five buildings (Table 1) and the alternative structural options considered (Table 2) was measured using the life-cycle assessment (LCA) model CLEAR[20].

CLEAR is based on the LCA standards BS EN ISO 14040:2006[21] and 14044:2006[22] which are the principal generic standards governing the use of LCA. The CLEAR model has been developed using the GaBi 4 software platform[23].

In the context of building and construction LCA, standards being developed by CEN TC350 are intended to provide a harmonised approach to the measurement of the environmental impacts of construction products and whole buildings across the entire lifecycle. These new standards are applicable to all building types. Amongst these standards is BS EN 15804:2012[24], the purpose of which is to harmonise existing environmental product declaration (EPD) schemes to a set of common rules, called product category rules (PCR). This standard

§ CO_2e is the measure that describes, for a given mixture and amount of greenhouse gases, the amount of CO_2 that would have the same global warming potential (GWP), when measured over a specified timescale (generally, 100 years).

Table 1: The five commercial buildings studied

Building type and location		Description (base case building)	GIFA[a] (m²) / Storeys	Capital construction cost (£k) [Pricing date]	Unit capital construction cost (£/m²)[a]
	Distribution warehouse Stoke-on-Trent	Steel portal frame Built-up steel wall and roof cladding systems 15% roof-lights Gas-fired radiant heating Completed in December 2007	35,400 single storey with 2-storey attached office block	19,441 [Q3 2009]	549
	Supermarket Stockton-on-Tees	Braced steel frame Upper floor (back of house) structural metal decking Mezzanine – plywood boarding on rolled steel joists Aluminium standing seam roof Composite steel panel external walls Completed in May 2008	9,393 single storey with mezzanine front of house; two storey back of house	16,400 [Q4 2009]	1,746
	Secondary school Knowsley	Structural steel frame supporting precast concrete floor slabs A combination of timber cladding, aluminium curtain walling and terracotta rainscreen Mechanically ventilated Completed December 2008	9,637 3 storeys	22,500 [Q2 2009]	2,335
	Office Central London	Fabricated cellular steel beams supporting a lightweight concrete slab on profiled steel decking Aluminium curtain walling Mechanically ventilated and cooled Completed in 2008	33,018 10 storeys and 2 basement levels	61,700 [Q2 2010]	1,869
	Mixed-use (hotel and office building) Manchester	Steel frame with Slimdek floors Aluminium curtain-walling and rainscreen, ceramic granite cladding and external render Mechanically ventilated and cooled Completed in 2011	18,625 17 storeys	36,700 [Q4 2010]	1,970

[a] Gross internal floor area

Table 2: Alternative structural forms considered

Building type	Base case structure		Alternative structural option 1		Alternative structural option 2	
	Description	Structure[a] unit cost (£/m²)	Description	Structure[a] unit cost (£/m²)	Description	Structure[a] unit cost (£/m²)
Distribution warehouse	Steel portal frame	65	Glulam beams and purlins supported on concrete columns	118	Steel portal frame with northlights	85
Supermarket	Braced steel frame CFA piles	107	Glulam frame Upper floor concrete slab on steel deck Mezzanine: Glulam beams supporting timber decking CFA piles	141	Braced steel frame Upper floor concrete slab on metal deck Mezzanine: light steel supporting timber decking North light roof profile in retail area Steel H-piles	117
Secondary school	Steel frame supporting precast hollow core concrete units Precast concrete piles	203	*In-situ* 350mm concrete flat slab Precast concrete piles	182	Steel frame supporting a concrete slab on a profiled steel deck Steel H-piles	190
Office	Fabricated cellular steel beams supporting a lightweight concrete slab on a profiled steel deck	316	350mm thick post-tensioned concrete flat slab	377	-	-
Mixed-use (hotel and office building)	Steel frame with Slimdek floors	411	Concrete flat slab: 260mm thick slab in office floors 250mm thick slab in hotel floors	355	Cellular steel beams supporting lightweight concrete slab on steel decking	318

[a] Frame and upper floors

had not been published when Target Zero was undertaken.

The CLEAR model has successfully undergone a third party critical review to the relevant ISO standards on LCA by Arup. This review concluded that the CLEAR methodology and its representation in the GaBi software has been undertaken in accordance with the requirements of ISO 14040 and ISO 14044. Furthermore Arup are confident that the data quality rules used to select the material life cycle inventory data in the CLEAR GaBi model are also consistent to these standards and the goals of the methodology. The CLEAR model assumptions were also reviewed and approved by AECOM.

The scope of the embodied carbon assessment performed using the CLEAR model is shown in Table 3.

As the basis of the cost plans, Cyril Sweett generated bills of quantities for all five buildings defined in Table 1 and each alternative structural form defined in Table 2. These were then used to derive the material input quantities to the CLEAR model.

The main building elements were accounted for, including:

- foundations and ground floor slab, including associated fill materials
- superstructure (including all structural columns and beams, cladding rails and fire protection)
- upper floors and staircases
- walls (external and internal partition walls)
- roof
- windows, rooflights and glazed curtain walling
- drainage
- external works (warehouse and supermarket studies only)

Items excluded from the analysis were access ladders and gantries, internal doors, internal fit-out, lifts, wall, floor and ceiling finishes and building services such as water, heating and cooling systems.

Table 3: Scope of assessment of the CLEAR model

Life cycle stage	Description
Material/product manufacture	Included – see below
Transport (factory gate to site)	Included – average gate-to-site transport distances for the UK were based on the Department for Transport's (DfT) Road Freight Statistics[25]. All transport was assumed to be by road with vehicles assumed to be loaded to 85% of capacity. Empty return trips were conservatively assumed.
Construction waste	Included – based on WRAP data[26]
Transport of waste from site	Included as above
Construction process	Included - no specific data or information on construction site impacts was available for the five buildings studied. Instead information, in terms of diesel and electricity consumption data, from two published sources[27,28] were used and these data scaled to the size (GIFA) of the buildings studied. Insufficient data were available to differentiate site construction impacts between the different structural options assessed
Maintenance	Excluded - maintenance regimes and their associated impacts for different structural options are not well documented nor are they likely to be significant for structure
Demolition/ deconstruction	Excluded – insufficient data are currently available to quantify demolition impacts robustly
End-of-life recovery rates	Included

Carbon emission factors

The quality of comparative embodied carbon assessments is, to a large extent, dependent upon the scope, accuracy and consistency of the carbon emissions factors used.

Most carbon emissions factors used to assess the embodied carbon impact of buildings are based on a cradle-to-gate scope, i.e. they only include embodied carbon emissions up to the point where the product leaves the factory gate. The Inventory of Carbon and Energy (ICE) developed by the University of Bath[29] uses this limited basis for its embodied carbon emissions factors. However, the ICE does acknowledge that a 'well rounded study' should address the full life cycle and addresses the recycling of metals in Annex A of the ICE.

Importantly, cradle-to-gate assessments exclude downstream impacts including transport to site, construction activities, maintenance and end-of-life activities including deconstruction and, most importantly, the reuse and recycling of materials.

There are several sources of life cycle inventory (LCI) data available that allow the calculation of embodied carbon (CO_2e) per unit weight of material. Most of the embodied carbon emission factors used in CLEAR were sourced from PE International's 'Professional' and 'Construction Materials' GaBi databases. PE international are leading experts in LCA and have access to comprehensive materials LCI databases.

Steel data were provided by the World Steel Association and are based on 2000 average production data. The worldsteel LCA study[30] is one of the largest and most comprehensive LCA studies undertaken and has been independently reviewed to BS EN ISO standards 14040 and 14044.

Steel data from GaBi were not used because at the time, they were based on German production and therefore were not necessarily representative of UK or European data. Furthermore some products, including structural steel sections, were not included within the GaBi databases. Since the Target Zero study ended, the worldsteel data have become available in the GaBi databases.

The embodied carbon results were reported in terms of total greenhouse gas emissions in carbon dioxide equivalents (CO_2e). In this study, an index of greenhouse gases developed by the University of Leiden[31] has been used. This index has been updated with the latest characterisation factors from the Intergovernmental Panel on Climate Change (IPCC).

The embodied carbon emission factors for the principal structural materials used in the assessments are shown in Table 4.

Table 4: Carbon emissions factors used in the assessments

Material	Data source	End-of-life assumption	Source	Total lifecycle CO_2 emissions (tCO_2e/t)
Fabricated steel sections	worldsteel (2002)[30]	99% closed loop recycling, 1% landfill	MFA of the UK steel construction sector[32]	1.009
Steel purlins	worldsteel (2002)	99% closed loop recycling, 1% landfill	MFA of the UK steel construction sector	1.317
Steel reinforcement	worldsteel (2002)	92% closed loop recycling, 8% landfill	MFA of the UK steel construction sector	0.820
Concrete (C30/37)	GaBi LCI database 2006 – PE International[23]	77% open loop recycling, 23% landfill	Department for Communities and Local Government[33]	0.139
Glulam	GaBi LCI database 2006 – PE International	16% recycling, 4% incineration, 80% landfill	TRADA[34]	1.10

End-of-life impacts

The fate of materials from buildings after they are demolished can have a significant effect on whole lifecycle emissions. For example, assumptions made about the end-of-life disposal of bio-based products including their decomposition within landfill and any resulting methane emissions are significant and should be taken into account in a robust, whole-life embodied carbon assessment.

End-of-life data used in the CLEAR model were based on current material performance, using published data where these are available, rather than based on future possible end-of-life scenarios. Table 4 shows the end-of-life assumptions made in the CLEAR model for the principal construction materials.

There is a range of methodologies that can be used to assess the benefits of recycling. The CLEAR model follows the guidelines for allocation procedures set out in ISO 14044 to calculate the benefits of recycling. Materials that are recycled are assumed to displace or save the production of new materials (which could be the same or a different material) and are given 'credits' equivalent to the impacts avoided. This approach is applied to all materials within the model as followes:

- Where one product system is recycled to form another product system with different inherent properties, this is known as open loop recycling. An example of this is crushing concrete to produce hardcore
- Other materials are capable of being recycled without loss of quality. This is known as closed loop recycling. An example of this is steel which is recycled (remelted) into new steel products without any loss of properties or quality

The recent CEN standard on rules for producing environmental product declarations for construction products BS EN 15804 allows for the inclusion of the benefits of reusable and recyclable products, using the same ISO LCA standards, via the use of Module D. There are specific requirements in BS EN 15804 to avoid double accounting the benefits of recycling in both production (recycled content) and at end-of-life (recycling rate) phases of the lifecycle. The CLEAR model also avoids double accounting of recycling benefits, albeit using a different approach, but overall results would be similar to that using BS EN 15804.

The efficiency of recycling was set in the CLEAR model using an efficiency factor for each material, to reflect whether the material follows closed or open loop recycling characteristics. Efficiency factors can be calculated using methods outlined in ISO LCA standards[21, 22], such as value correction or mass allocation. For materials that are closed-loop recycled, the efficiency factor was taken as 100%, meaning that there is no loss of material property during recycling. For materials that are open-loop recycled, the efficiency factor was calculated to take account of the loss in properties incurred through the recycling process.

Embodied carbon results

Figure 2 shows the total embodied carbon emissions for each building and for each alternative structural option (as defined in Tables 1 and 2).

Figure 3 shows the same data but with the total embodied carbon emissions normalised to gross internal floor area (GIFA). The normalised carbon emissions vary between 234kgCO_2e/m² for the distribution warehouse (Base Case) up to 506kgCO_2e/m² for the high-rise office building (Structural option 2).

Figure 4 shows the variation in the embodied carbon in the frame and upper floors for each building normalised to the

Figure 2
Total embodied carbon emissions for each building and structural alternative

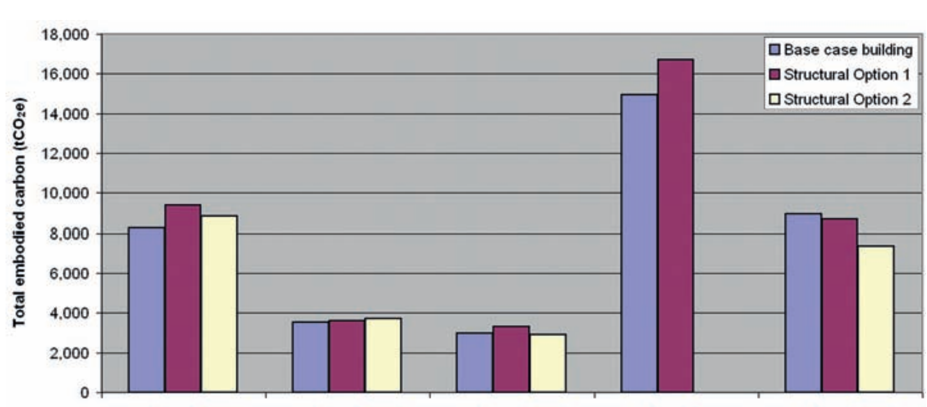


Figure 3
Total embodied carbon emissions normalised to GIFA

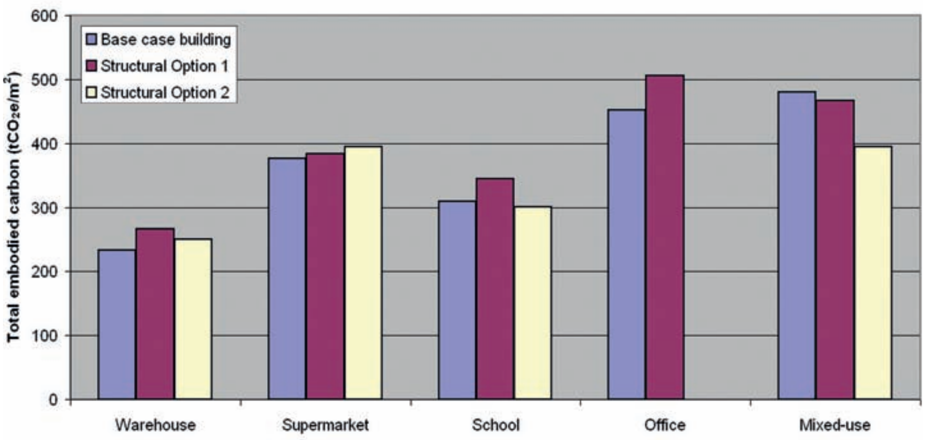
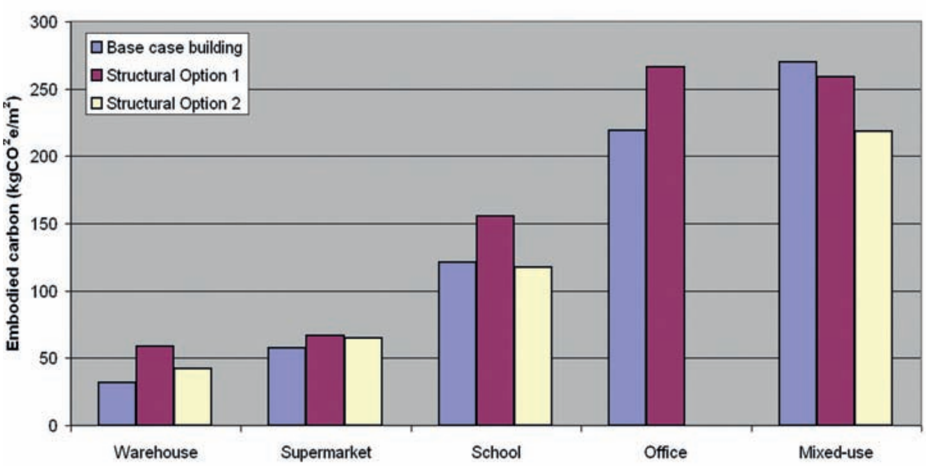


Figure 4
Embodied carbon in frame and upper floors normalised to GIFA



gross internal floor area. The normalised carbon emissions vary between 32kgCO_2e/m² for the distribution warehouse (Base Case) up to 270kgCO_2e/m² for the mixed-use building (Base Case).

The low rise buildings (warehouse and supermarket) show similar results, as do the high rise buildings assessed (office and mixed-use). The school building (three storeys) lies midway between the two datasets.

The frame and upper floors in the low-rise buildings represent 14% to 22% of the total building embodied carbon. For the high-rise buildings, the frame and upper floors make up 48% to 66% of the total impact.

As part of the Target Zero programme, detailed breakdowns of the embodied carbon by building element and by material was undertaken. These results are presented in the Target Zero design guides. Here we report only the detailed results for the distribution warehouse and office building due to space constraints. Figure 5 shows the breakdown in total embodied carbon emissions for the office Base Case building by major elements.

Figure 6 shows the same breakdown for the distribution warehouse Base Case building.

Table 5 shows the relative embodied carbon contribution of transport (including gate-to-site, excavated material taken off-site and materials for recovery/recycling following demolition) and on-site construction impacts for each building.

Impact of structure on operational carbon emissions

Figure 7 shows the variation in operational carbon emissions (by energy use) for the office building. The energy demand, and associated operational carbon emissions, for hot water, lighting, fans and pumps and small power are identical for all scenarios modelled. The predicted carbon emissions from heating and cooling show little variation between the two structural forms modelled (also see Appendix 1).

The potential for utilising thermal mass in multi-storey buildings was also investigated by removing the ceilings. The predicted operational carbon emissions confirmed previous research[39] which showed that the benefits of thermal mass were very similar for typical steel and concrete framed commercial buildings. In both the office and mixed-use buildings studied, any cooling benefit of exposing the thermal mass in the floor slabs was more or less balanced by the extra heating demand for the additional volume generated by removing the ceilings. This is illustrated in Figure 8 which shows the net effect of these heating and cooling demand changes on the predicted Building Emission Rates (BERs) for the office building.

In general, the net effect of exposing the thermal mass in multi-storey, commercial buildings depends on the balance of the heating and cooling demands of the building. For the office building, the heating and cooling demands of the building were similar (cooling contributed 8% of the total operational carbon emissions and space heating contributed 10%) and therefore the net effect of exposing thermal mass is small. In buildings where the cooling demand is relatively low, the benefits of exposing the thermal mass is likely to be small and there may even be a net increase in carbon emissions due to the increased heating demand.

Table 5: Summary of transport and on-site construction activity impacts

Building	Percentage of total embodied carbon impact (%)	
	Transport	On-site construction activities
Distribution warehouse	8.2 – 9.0	1.0 – 1.1
Supermarket	8.7 – 9.5	0.7
Secondary school	6.5 – 7.4	9.4 – 10.7
Office building	12.6 – 14.1	4.2
Mixed-use building	4.3 – 4.9	13.0 – 15.8

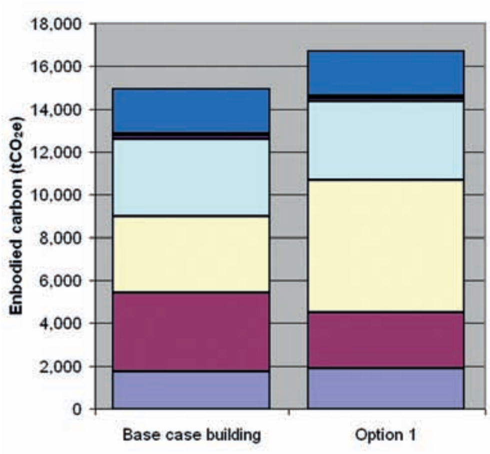


Figure 5
Breakdown of embodied carbon by element – office building

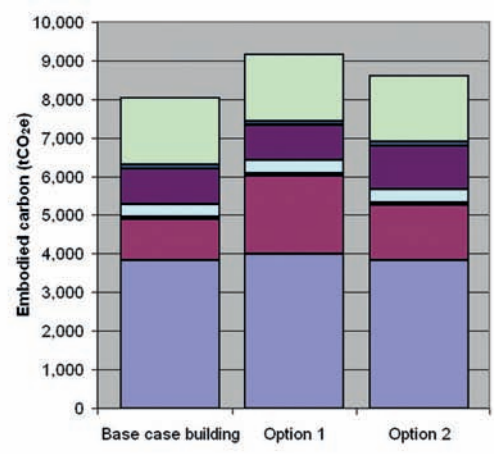


Figure 6
Breakdown of embodied carbon by element – distribution warehouse

Figure 7
Breakdown of operational carbon emissions by energy use – office building

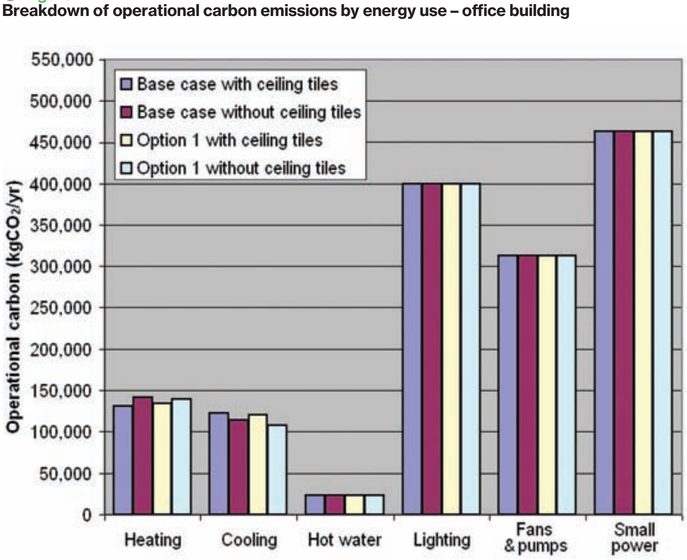


Table 6: Total embodied and operational carbon emissions (Base Case Buildings)

Building	Total embodied carbon emissions (tCO_2e)	Total operational carbon emissions (tCO_2 pa)	Ratio[a] – Embodied: Operational (years)
Distribution warehouse	8,257	1,059	7.8
Supermarket	3,528	699	5.0
Secondary school	2,981	355	8.4
Office building	14,937	1,455	10.3
Mixed-use building	8,947	1,186	7.5

[a] Note that the units for operational carbon emissions (tCO_2) differ from those used for embodied carbon emissions (CO_2e)

Table 7: Ratio - Annual operational carbon: Embodied carbon (years)

Operation carbon reduction target	Distribution warehouse	Supermarket	Secondary school	Office	Mixed-use
Part L 2006 compliant base case building	7.8	5.0	8.4	10.3	7.5
25% reduction in regulated carbon emissions (Part L 2010)	9.9	6.3	10.5	12.4	8.9
44% reduction in regulated carbon emissions	12.5	7.7	13.0	14.6	10.2
70% reduction in regulated carbon emissions	19.4	11.3	19.4	19.6	13.0
100% reduction in regulated carbon emissions	53.8	24.0	44.2	32.1	18.9

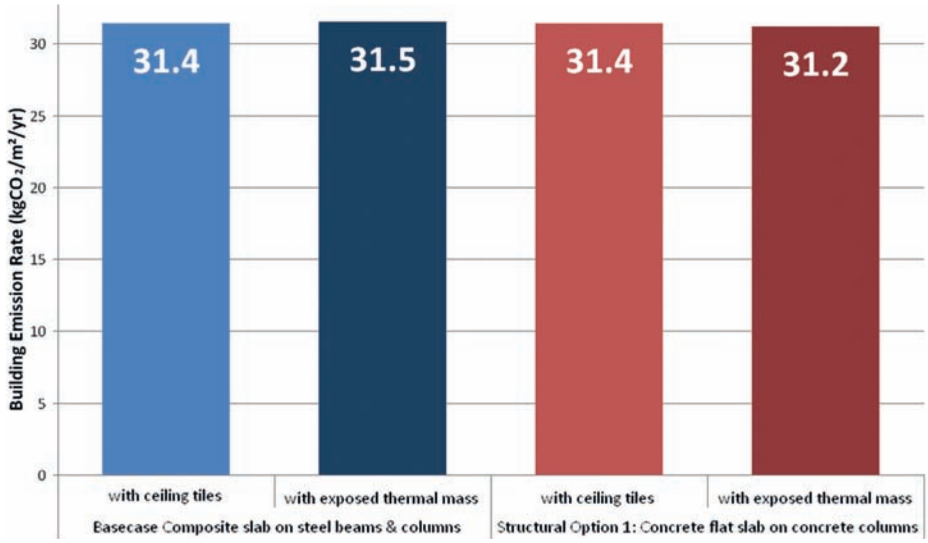
The structural form can also influence the floor-to-floor height and the resulting enclosed volume will also affect the heating/cooling demand balance for the building. Designers should also consider the cost, aesthetic and acoustic implications of removing ceilings to mobilise thermal mass in commercial buildings.

Embodied and operational carbon impacts

Table 6 shows the total embodied and operational carbon emissions for each of the five Base Case buildings, i.e. Part L 2006 compliant buildings, and the ratio (Embodied:Operational carbon emissions) in terms of years.

It is clear however that as operational carbon reductions are achieved, the relative significance of embodied carbon impacts from buildings will increase. Table 7 shows the ratio between the embodied carbon and the annual predicted operational carbon emissions for each building studied (Base Case) and for different possible future operational carbon reduction targets. The table shows that for the Part L (2006) compliant school building for example, the embodied carbon is exceeded after 8.4 years of building operation. This ratio increases to 44.2 years under the scenario of 100% reduction in regulated carbon emissions. These results are indicative only however since, as UK energy production is decarbonised in the future, the embodied carbon of buildings should also reduce.

Figure 8
Building Emission Rates (BERs) for different office building structural options



"Designers should also consider the cost, aesthetic and acoustic implications"

Embodied carbon and cost KPIs

Table 8 gives the normalised (to GIFA) construction cost and embodied carbon results for the five Base Case buildings studied. The ratios of embodied carbon and construction cost are also provided.

Table 9 presents the same metrics but for the structure (frame and upper floors).

Table 8: Base Case Buildings: Total building construction cost and embodied carbon (normalised to GIFA)

Building	Total construction cost (£/m²)	Embodied carbon ($kgCO_2e/m^2$)	Ratio ($kgCO_2e$/£)
Distribution warehouse	549	233	0.42
Supermarket	1,746	376	0.22
Secondary school	2,335	309	0.13
Office building	1,869	452	0.24
Mixed-use building	1,970	480	0.24

Table 9: Base Case Buildings: Total structure (frame and upper floors) construction cost and embodied carbon (normalised to GIFA)

Building	Structure cost (£/m²)	Embodied carbon ($kgCO_2e/m^2$)	Ratio ($kgCO_2e$/£)
Distribution warehouse	65	32	0.49
Supermarket	107	58	0.54
Secondary school	203	121	0.60
Office building	316	219	0.69
Mixed-use building	411	270	0.66

Conclusions

This paper has summarised the results from a comparative embodied carbon assessment of new commercial buildings focusing particularly on different structural forms. Key conclusions from this study include:

- Embodied carbon assessment of buildings and construction products is in its infancy. Reliable embodied carbon emission factors and assessment tools are emerging but further work is required
- Embodied carbon assessments should be based on life cycle assessment (LCA) principles and use relevant CEN and ISO standards
- Cradle-to-gate embodied carbon assessments exclude important 'downstream' impacts including transport, construction site impacts, deconstruction and reuse, recycling and recycling potential. Only studies that adopt a whole-life (cradle-to-grave) approach are consistent with longer term sustainable development goals
- Based on the buildings studied, operational carbon emissions are not significantly affected by structural form
- For low-rise buildings, the overall embodied carbon impact is dominated by the foundations, ground floor slab and external works
- For medium to high-rise buildings, the embodied carbon impact is dominated by the frame and upper floors
- Based on the buildings studied, optimised structural steel solutions yielded the lowest cost and lowest embodied carbon compared to the alternative structural options considered

Acknowledgments

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Appendix 1: Operational carbon results

A dynamic thermal model of each building was developed using the IES software suite[35] and the model fine-tuned to just pass Part L2A (2006) of the Building Regulations[36]. For consistency, all five buildings were assessed using CIBSE Manchester 2005 weather tapes[37].

Dynamic thermal modelling was then used to predict the operational energy performance of each building following the introduction of a range of practicable energy efficiency measures and LZC technologies. The predicted energy costs, coupled with the capital and maintenance costs, were then used to derive a net present value (NPV) for each measure over a 25-year period. This period was selected to represent the maximum likely timescale after which full asset replacement would have to be considered for the LZC technologies analysed. NPVs were expressed as a deviation from that of the Base Case building, thus some energy efficiency measures and LZC technologies have negative NPVs as they were found to save money over the 25-year period considered.

The cost data and the energy modelling results were then combined to provide each energy efficiency measure and LZC technology with a cost-effectiveness measure in terms of 25-year NPV per kg of CO_2 saved relative to the Base Case building performance. Energy efficiency measures and LZC technologies were then ranked in terms of this cost-effectiveness measure to derive the most cost effective routes, i.e. combinations of compatible energy efficiency and LZC technologies, to achieve 25%, 44%, 70%, 100% (BER =0) carbon reduction requirements (relative to Part L 2006) and true zero carbon. Setting of these reduction targets predated the Government's consultation on policy options for new non-domestic buildings.

The most cost effective routes to achieve these reduction targets, together with the associated capital and whole-life costs are given in the Target Zero design guides.

As part of this analysis, the impact of the different structural forms on operational carbon emissions was also modelled. Where relevant (office and mixed-use buildings) the buildings were modelled both with and without suspended ceilings. This was done to expose the soffits of the upper floors allowing the thermal mass in the floor slabs to be more effectively mobilised.

The influence of the different structural forms studied (see Table 2) was found to have only a very small impact on the predicted operational carbon emissions from all five buildings. For the school, office and mixed-use buildings, the impact of structural form (with and without suspended ceilings) on regulated annual carbon emissions is predicted to vary by less than 1%. For the low rise warehouse and supermarket buildings, the variation was slightly greater at around 3%. This variation is due mainly to the different depths of the alternative structural options and the corresponding internal volumes.

Increased storey heights result in greater heat losses and therefore higher heating but lower cooling requirements. The interaction of these impacts is complex and therefore the predicted net effect on the total operational carbon emissions is variable but generally small.

Table A1 gives the building emission rate (BER), the unit capital construction cost, the predicted total operational carbon emissions (normalised to GIFA) and the ratio of annual operational carbon emissions to capital construction cost.

Table A1: Operational carbon emissions results (Base Case Buildings)

Building	BER[a] ($kgCO_2pa/m^2$)	Capital construction cost (£/m²)	Total operational carbon emissions ($kgCO_2pa/m^2$)	Ratio (tCO_2pa/£M)
Distribution warehouse	23.9	549	29.9	54.5
Supermarket	55.5	1,746	74.4	42.6
Secondary school	27.3	2,335	36.8	15.8
Office	31.4	1,869	44.1	23.6
Mixed-use	42.8	1,970	63.7	32.3

[a] BER = Building Emissions Rate which includes only regulated emissions under Part L of the Building Regulations

Appendix 2: BREEAM results

The objective of this aspect of Target Zero was to determine the most cost-effective routes to achieving a 'Very Good', 'Excellent' and 'Outstanding' BREEAM (2008) rating for the five buildings described in Table 1.

Base Case buildings were defined based on the specification and location given in Table 1 and on typical construction practice. As for the operational carbon assessment, the Base Case buildings were Part L (2006) compliant.

Reflecting the influence of location and other factors on the achievable BREEAM score, different scenarios were modelled including different locations and site conditions and different design and contractor assumptions.

All the credits that required additional work to achieve were attributed with a capital cost and assigned a 'weighted value' by dividing the capital cost of achieving the credit, by its credit weighting[a]. Credits were then ranked in order of cost-effectiveness and these rankings used to define the most cost-effective routes to achieving 'Very Good', 'Excellent' and 'Outstanding' BREEAM (2008) ratings for each of the proposed buildings and scenarios.

Table A2 shows the capital cost increase or uplift for the Base Case buildings defined in Table 1 to achieve 'Very Good', 'Excellent' and 'Outstanding' BREEAM (2008) ratings.

Within BREEAM the only credits directly related to the structure are the materials credits that address environmental impact (Mat 01) and responsible sourcing of construction materials (Mat 03).

Mat 01 credits are based on the Green Guide to Specification[38] ratings. However the superstructure is not specifically included either within the Mat 01 scope of assessment or within the Green Guide. According to BRE, this is because it is not possible to provide either representative functional units for these elements or comparable specifications. Upper floors are included within the Green Guide and Table A3 gives the Green Guide ratings for upper floor systems commonly used in commercial and industrial buildings.

Under Mat 03 the structural frame is one of nine building elements assessed.

Table A2: BREEAM cost uplift results

Building	Capital cost uplift (%) to achieve BREEAM		
	Very Good	Excellent	Outstanding
Distribution warehouse	0.04	0.4	4.8
Supermarket	0.2	1.8	10.1
Secondary school	0.2	0.7	5.8
Office	0.1	0.8	9.8
Mixed-use	0.2	1.6	5.0

Table A3: Green Guide to Specification rating for common upper floor constructions

Specification	Green Guide rating
Power floated *in-situ* reinforced concrete floor slab	C
Power floated post-tensioned *in-situ* reinforced concrete floor slab	A
Power floated *in-situ* reinforced concrete slab on 'deep' profiled metal decking	A+
Power floated *in-situ* reinforced concrete slab on 'shallow' profiled metal decking	A+

[a] Under BREEAM, credits in different sections of the assessment, e.g. energy, materials, etc. are given different weightings.

References

1 www.targetzero.info (accessed June 2012)

2 DECC, (2008) Climate Change Act 2008; London: The Stationary Office Ltd

3 Department for Communities and Local Government, (2009), *Zero carbon for new non-domestic buildings; Consultation on policyoptions,* London: DCLG, November 2009, 67pp

4 Department for Communities and Local Government, (2011) *Zero carbon for new non-domestic buildings; Phase 3 final report,* July 2011, London: DCLG, 121pp

5 *Allowable solutions for tomorrow's new homes: Towards a workable framework,* Zero Carbon Hub, July 2011

6 Smith B. P.: (2008) Whole-life carbon footprinting, *The Structural Engineer,* March, 86/6, pp. 15-16

7 Anderson J. E. and Silman R.: (2009) The role of the structural engineer in green building, *The Structural Engineer,* 87/3, pp. 28-31

8 Various authors, (2009) Themed issue on embodied carbon, *Proceedings of the Institution of Civil Engineers – Energy,* 164/EN4, pp. 134-206

9 Sturgis S. and Roberts G.: (2010) 'Redefining zero: carbon profiling as a solution to whole life carbon emission measurement in buildings', *RICS Research Report,* May 2010, 47pp

References (cont.)

► 10 Hammond G. P. and Jones C. I.: (2008) 'Embodied energy and carbon in construction materials', *Proceedings of the Institution of Civil Engineers – Energy,* 161/EN2, pp. 87-98

► 11 Menzies G. F., Turan S. and Banfill P. F. G.: (2007) 'Life-cycle assessment and embodied energy: a review', *Proceedings of the Institution of Civil Engineers – Construction Materials,* 160/CM4, pp.135-143

► 12 Burridge J.: (2010) 'Embodied CO_2 in construction', *The Structural Engineer,* 88/18, pp. 10-12

► 13 Vukotic L., Fenner R. A. and Symons K.: (2010) 'Assessing embodied energy of building structural elements', *Proceedings of the Institution of Civil Engineers,* 163/ES3, pp. 147-158

► 14 Kaethner S. C. and Yang F.: (2011) 'Environmental impacts of structural materials – Finding a rational approach to default values for software,' *The Structural Engineer,* 89/13, pp. 24-30

► 15 Knight D. and Addis B.: (2011) 'Embodied carbon dioxide as a design tool – a case study', *Proceedings of the Institution of Civil Engineers, Civil Engineering,* November, 164, pp. 171-176

► 16 *Embodied carbon Sustainable Offices: a supplementary report,* Report prepared on behalf of the South West Regional Development Agency by Halcrow Yolles, 2010

► 17 Allwood J. and Cullen J. M.: (2012) *Sustainable materials with both eyes open,* Cambridge, UK: UIT Cambridge Ltd

► 18 Barrett N.: (2007) 'Structural design benefits sustainability', *The Structural Engineer,* 1 May, 85/9, pp. 25-26

► 19 *A short guide to embodied carbon in building structures,* (2011) London: The Institution of Structural Engineers, Sept, 18pp

► 20 Griffin A., Millar I., Avery N., Coleman N. and Hodgson P.: (2011) 'CLEAR – An LCA model for construction', *LCM Conference 2011,* Berlin, Germany

► 21 ISO 14040:2006, *Environmental management – Life cycle assessment – Principles and framework,* Geneva: ISO

► 22 ISO 14044:2006, *Environmental management – Life cycle assessment – Requirements and guidelines,* Geneva: ISO

► 23 GaBi LCA software developed by PE International www.gabi-software.com (accessed June 2012)

► 24 British Standards Institute, (2012) BS EN 15804:2012, *Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products,* London: BSI

References (cont.)

► 25 Department for Transport (2008), *Transport Statistics Bulletin – Road Freight Statistics 2007,* London: DfT

► 26 Burton E. and Friedrich N.: (2008), *Net Waste Tool Reference Guide v 1.0,* WRAP (accessed July 2012)

► 27 *Life cycle assessment – One Kingdom Street, Paddington Central, London,* (PDF of project report) Deloitte dcarbon8, August 2007 (contained in unpublished report – Skanska)

► 28 Fieldson R. and Siantonas T.: (2008) 'Comparing methodologies for carbon footprinting distribution centres', *COBRA 2008 – RICS Construction and Building Research Conference, DIT Dublin,* London: RICS, pp. 1-26

► 29 Hammond G. and Jones C. (2011) *Embodied carbon: The inventory of carbon and energy (ICE). BSRIA BG 10/2011* (ed. F Lowrie and P Tse), England: University of Bath/BSRIA, 136pp

► 30 World Steel Association (2011) *World Steel Association Life Cycle Inventory Study for Steel Products,* Brussels, Belgium: WSA

► 31 Institute of Environmental Sciences (CML), Leiden University (2007) *Handbook on impact categories 'CML 2001' Global Warming Potential (GWP 100 years),* The Netherlands: IES, Leiden University (http://cml.leiden.edu/research/industrialecology/researchprojects/finished/new-dutch-lca-guide.html) (Accessed July 2012)

► 32 Ley J.: (2003) 'An environmental and material flow analysis of the UK steel construction sector', *DEng thesis,* University of Wales

► 33 Department for Communities and Local Government (2007) *Survey of arisings and use of alternatives to primary aggregates in England, 2005; construction, demolition and excavation waste,* Final Report on behalf of the DCLG by Capita Symonds Ltd, in association with WRc plc

► 34 TRADA, (2008) 'Recovering and minimising wood waste', *TRADA Technology wood information sheet 2/3 Sheet 59',* revised June 2008

► 35 www.iesve.com (accessed June 2012)

► 36 Office of the Deputy Prime Minister (2006) *Approved Document L2A: Conservation of fuel and power (New buildings other than dwellings)* (2006 edition), London: ODPM

► 37 CIBSE TRY/DSY Hourly Weather Data Set – Manchester (2005)

► 38 Anderson J., Shores D. and Steele K.: (2009) *The Green Guide to Specification,* 4th ed., Watford: BRE and Oxford Brookes University

► 39 (2007) *Thermal Mass Performance in Commercial Office Buildings,* Faber Maunsell, (Unpublished confidential report – Available from TATA/Corus)