Case study on the whole life carbon cycle in buildings

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Abstract: The potential for reducing greenhouse gas emission from buildings comes from both operational and embodied emissions. To date the focus has been on reducing the operational element, although, it is suggested that it is also important to consider early embodied carbon reductions.
This paper describes a case study on the whole life carbon cycle of a building in the UK. Specific issues addressed are the relationship between embodied carbon (Ec) and operational carbon (Oc), the proportions of Ec from the structural and non-structural elements, carbon benchmarking of the structure, the value of 'cradle to site' or 'cradle to grave' assessments and the significance of the timing of emissions during the life of the building.
The case study indicates that Ec can be an important consideration and that the structure was responsible for more than half of the Ec.
An indicative structural benchmark for the building is between 260kgCO_2/m^2 and 286kgCO_2/m^2.
Weighting of future emissions appears to be an important factor to consider. The PAS 2050 reduction factors had only a modest effect but weighting to allow for future decarbonisation of the energy supply had a large effect.

Keywords: *Embodied carbon, Carbon emission, Building, Operational carbon,* CO_2.

1. Introduction

The potential for reducing greenhouse gas emission from buildings comes from both operational emissions, produced by buildings during use, and embodied emissions, produced during manufacture of materials and components, and construction and demolition of buildings.

To date the UK government has focused attention on reducing the, apparently, larger operational element. This is reflected in the current methods of environmental assessment of buildings, which allow the highest environmental ratings to be achieved without any consideration of embodied emissions. This, together with the lack of readily available and usable data on embodied emissions, has hampered the consideration of embodied carbon during building design.

UK Building Regulations are employing a phased approach to increasing energy conservation criteria, resulting in reduced carbon emissions, in the period up to 2020. However, this only applies to operational carbon.

In terms of meeting the UK carbon reduction targets of 34% by 2020 and 80% by 2050 (measured against the 1990 baseline), it may be equally, if not more, important to consider early embodied carbon reductions, rather than just future operational reductions. Future decarbonisation of energy supply and more efficient lighting and M&E equipment installed in future refits is likely to significantly reduce operational emissions, lending further weight to this argument. Methods of emission discounting to evaluate the present value of future emissions, may allow more realistic comparisons to be made between the embodied and operational elements.

Currently, there is lack of a consistent and accepted approach to the calculation of embodied emissions, the relationship and interaction between the embodied and operational elements is not well understood, and there is considerable uncertainty and variability in the available information on emission factors for building materials and processes. Work under the European Standards Mandate M350 'Sustainability of Construction Works' [1] seeks to remedy this by developing a harmonised approach to the measurement of embodied and operational environmental impacts of construction products and whole buildings, across the entire life cycle. At this stage, it is not clear when this will become available. In the meantime, PAS 2050 [2] is available, which builds on the life cycle analysis frameworks given in the BS EN 14040 [3] suite of standards and the Greenhouse Gas (GHG) Protocol [4] developed by the World Resources Institute and the World Business Council for Sustainable Development in 2004. PAS 2050 focuses exclusively on GHGs produced during the life of a product and services. However there is huge scope for variability in the data, life cycle boundaries selected, and assumptions made [5].

This paper describes a case study on the whole life carbon cycle of a book storage building in the UK. This is part of a research project aimed at producing data on embodied carbon for different types of building, components and forms of construction to assist designers in optimising building designs and minimising carbon emissions.

The paper investigates the following specific issues:

- the relationship between embodied carbon emissions (Ec) and operational carbon emissions (Oc)
- the proportions of Ec from the structural and non-structural elements, in order to determine the relative importance of Ec from the structure and to provide data for carbon benchmarking
- how 'cradle to site' and 'cradle to grave' based assessments compare
- the significance of considering when emissions occur during the life of the building.

2. Methodology

2.1. Description of the case study building

The case study building is a book storage facility, completed in October 2010, with a total internal floor area of 11,578m^2, designed to house around eight million volumes, in carefully regulated internal temperature and humidity conditions. It has a steel framed structure on mass concrete foundations, in-situ concrete floor and precast concrete insulated sandwich cladding panels to the external walls. The 12m-high main storage chamber has insulated metal deck roof cladding and the lower 7m high section has a composite concrete and metal deck roof to support the building plant and equipment. The building is well insulated, with high thermal mass provided by the external wall panels, and is well sealed, achieving an on-site air test result of 1.6m3/h/m^2.

2.2. Assumptions and procedure

In the majority of cases, available emission factors are for CO_2, and do not include the full basket of greenhouse gases (GHGs). Therefore, this study is based on CO_2 emissions only. It is estimated [6] that, for most building materials, CO_2 represents the vast majority of GHGs (e.g., around 95%), although for plastics other GHGs are more significant. It is anticipated that as materials data evolves and becomes more comprehensive, factors including all GHGs will become available.

A building life of 60 years has been assumed for the purposes of this study.

Ec values include emissions from materials and components (‘cradle to gate’), transport to site and site construction (‘cradle to site’), three M&E refits at 15, 30 and 45 years, a general building refurbishment at 30 years, demolition, transport and end of life treatment for demolished materials. End of life treatment has been assumed to be based on the following hierarchy: recycled where possible (e.g., steel); downcycled to a usable but lower grade material (e.g., concrete); incinerate for energy generation (e.g., timber); landfill.

Ec values for structural elements and non-structural have been calculated separately to assess their relative importance and to provide information for structural benchmarking. These are then compared with predicted Oc. This information can be valuable when assessing where to concentrate effort most effectively to reduce emissions.

Both ‘cradle to site’ and ‘cradle to grave’ assessments are carried out. The former is more straightforward to establish at the design stage. It is, therefore, useful to investigate if the additional effort required for a ‘cradle to grave’ assessment produces very different overall results. In this study ‘cradle to site’ also included site construction.

Previous studies [7] have shown that lifetime Oc is generally larger than Ec. However, Oc occurs over the lifetime of a building (generally 60 to 100years), whereas the vast majority of Ec occurs at the start of a building’s life. In terms of the timeframe in which carbon reductions need to be made, it is possible that carbon savings made at the start of a building’s life could be more valuable than predicted savings in the future. The effect of future decarbonisation of energy supply could have a profound effect on future emissions, as could more efficient lighting and M&E equipment installed in future refits. It is argued [8] that the cost of measures to mitigate climate change increase for every year the measures are delayed. For these reasons two methods of weighting future emissions are investigated, which may allow more realistic comparisons to be made between EC and OC.

The first is based on PAS 2050 [2] which accounts for the reduced period emissions are present in the atmosphere during a 100-year assessment period and the weighting factor is given by Eq.(1). This is a simplified version of the approach outlined by the IPCC[9].

$$Weighting\ factor = \frac{\sum_{i=1}^{100} X_i(100-i)}{100} \quad (1)$$

Where i is the year in which emissions occur and X is the proportion of total emissions occurring in that year i.

The second approach is based on the UK Government Markal-Med model scenarios for decarbonisation of the electricity supply over the period 2010 to 2050 [10]. Mean values of the scenarios considered have been used to give reduction factors to be applied to each of the annual Oc and the future Ec. These factors apply to future electricity supply but for the purposes of this study they are applied to energy supply as a whole.

2.3. Operation emissions (Oc)

The predicted annual ‘Building Emission Rate’, provided by the building designers, is $20kgCO_2/m^2$. This gives a predicted annual Oc of $231tCO_2$ for the whole building.

2.4. Embodied emissions (Ec)

The process of determining embodied carbon, although simple in principle, is not straightforward in reality due to uncertainty and lack of information on emission factors for all the materials and processes involved. There is considerable variability between the currently available databases for emissions from materials alone and there are a plethora of software tools and online 'carbon calculators' available purporting to provide whole life assessments. In many cases it is unclear exactly where the assessment boundaries have been drawn and which data sources have been used.

For these reasons Ec in this case study has been assessed using the authors own estimates of embodied CO_2 for materials from 'cradle to grave' using 'as constructed' data. Reference has been made to published UK and global figures from a variety of sources to achieve this [11], [12], [13], [14], [15], [16], [17], [18].

2.5. Transport

Transport emissions were determined using the UK Government published figures [19] and actual travel distances from suppliers to site, where this was known. Distances could be determined for the majority of the large quantity materials, but estimates were made where this information was not available.

2.6. Construction and demolition

Emissions from construction and demolition works on site were assessed using UK Environment Agency base data [12], the actual construction period and an estimate of the period required for demolition.

3. Results

3.1. Relationship between Ec (structure and non-structure) and Oc

Table 1 shows the relationship between Ec(structure), Ec(non-structure) for the different scenarios considered in the study.

Table 1. Case study building: proportions of Ec and Oc

	unweighted		PAS 2050		PAS 2050 + Markal	
	Cradle to site	Cradle to grave	Cradle to site	Cradle to grave	Cradle to site	Cradle to grave
Ec						
structure	17%	18%	19%	18%	35%	35%
non-structure	10%	14%	12%	14%	22%	22%
sub total	27%	32%	31%	32%	57%	57%
Oc	73%	68%	69%	68%	43%	43%
Total	100%	100%	100%	100%	100%	100%

The range of Ec as a percentage of the total emissions was found to be 27% to 57%, with structure 17% to 35%. Ec(structure) was always greater than Ec(non-structure).

The two extreme cases are shown as pie charts in Fig. 1 and Fig. 2 together with calculated values of tCO_2.

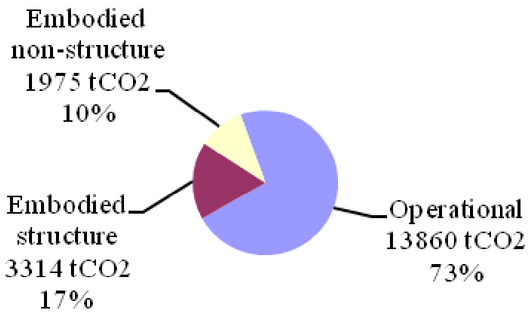


Figure 1. Case study building: embodied and operational emissions (cradle to site, unweighted)

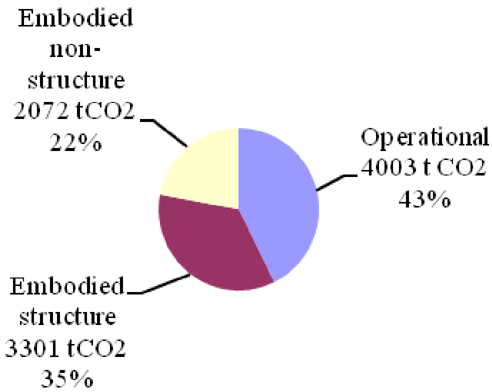


Figure 2. Case study building: embodied and operational emissions (cradle to grave, PAS 2050+Markal)

3.2. Structural benchmarkingc

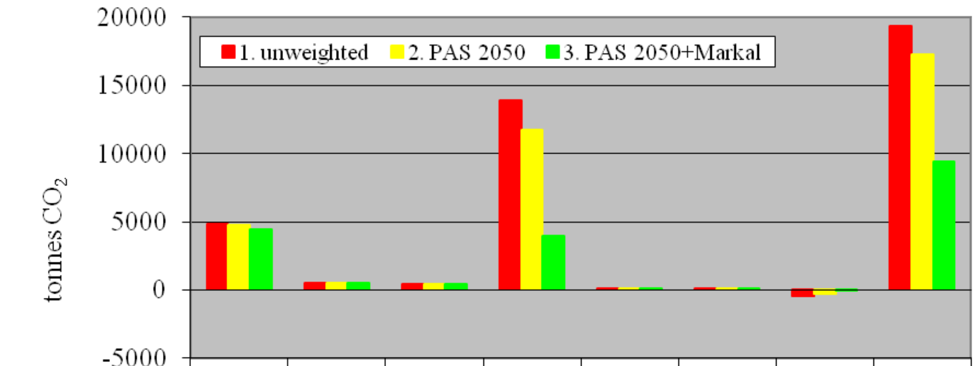
The range of values of Ec(structure)/m^2 of floor area was found to be between 260kgCO_2/m^2 ('cradle to grave', unweighted) and 286kgCO_2/m^2 ('cradle to site', PAS 2050 and PAS 2050+Markal).

3.3. 'Cradle to site' and 'cradle to grave'

Overall percentage differences between 'cradle to site' and 'cradle to grave' were relatively modest with a maximum of 5% in the unweighted case. The differences reduced if future emissions were weighted. However, for a comparison of individual materials, the end of life scenario can be significant, which indicates that material choices base purely on 'cradle to site', can give misleading results.

3.4. Weighting of future emissions'

Fig 3 shows CO_2 emissions for the case study building lifetime phases.



	Cradle to gate	Transport to/from site	Const-ruction	Oper-ation	Demo-lition	Transport to/from site	End of Life	Total cradle to grave
1. unweighted	4823	519	414	13860	52	102	-438	19332
2. PAS 2050	4756	518	413	11748	36	71	-307	17235
3. PAS 2050+Markal	4466	512	407	4003	2	4	-19	9376

Figure 3. Case study building: lifecycle CO_2 emissions

Applying the PAS 2050 reduction factors has a relatively small impact, whereas applying the PAS 2050+ Markal reduction factors has a large effect. The emission profiles over the building lifetime are clearly demonstrated in Fig. 4. This indicates that Ec is equivalent to approximately 23 and 25 years of Oc respectively in the unweighted and PAS 2050 cases and more than 60 years in the PAS 2050+Markal case.

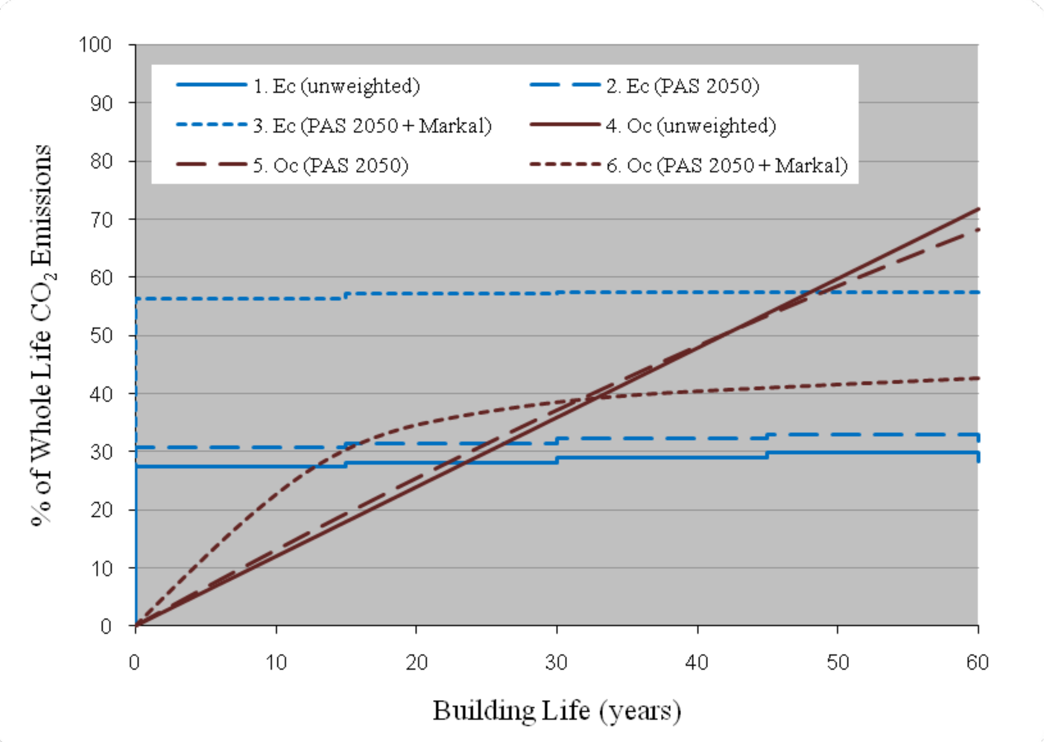


Figure 4. Case study building: Ec and Oc (cradle to grave) as a percentage of whole life emissions

4. Discussion and conclusions

The case study indicates that Ec can be an important consideration in lifecycle CO_2 emissions from buildings, and that in this case the structure was responsible for more than half of the Ec.

A review of other previous case studies [7] indicated that Ec varied between 79% and 108% of Oc for warehouse buildings and was as low as 2% for some other buildings. In this study the range was found to be between 27% and 57% demonstrating that different assumptions and boundary conditions can produce widely differing results and confirming the need for standardisation of Ec data and assessment methods. Assessment of lifecycle carbon emissions should not be considered a precise process due to the many uncertainties and assumptions that have to be made. Nevertheless, it can be a useful tool in assessing where emission reductions can be made most effectively.

An indicative structural benchmark for the building is between $260kgCO_2/m^2$ and $286kgCO_2/m^2$.

Oc in this case study is based on predicted values. The building was only completed in October 2010 and, therefore, there is currently no data available to assess their accuracy, although these will be available for future updates of the study.

Weighting of future emissions appears to be an important factor to consider. The PAS 2050 reduction factors, to reflect the period emissions are present in the atmosphere during a 100-year assessment period, had only a modest effect, possibly due to the relatively short building life. Longer life buildings would increase this effect but would conversely tend to reduce the Ec proportion of the whole life emissions. In contrast, weighting due to decarbonisation of the energy supply has a large effect, although a more detailed analysis of whether the rate of decarbonisation of the electricity supply will be reflected in the overall energy supply is required before the method used in this study can be validated. No attempt has been made to include discounting based on the cost of measures to mitigate climate change increasing with time but is considered that it would be useful to investigate this issue further.

It is considered that the results of this case study make a useful contribution to the overall bank of data on Ec in buildings.

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