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MATERIAL QUANTITIES AND EMBODIED CARBON IN EXEMPLARY LOW-CARBON CASE STUDIES

C. De Wolf[1]*, K. Bird[2], J. Ochsendorf[1]

[1] MIT, 77 Massachusetts Ave, Cambridge, MA 02139, USA
[2] Helionix Designs, Pines Garden, Beach Road, St Margaret's Bay, Dover, Kent CT15 6DZ, UK
*Corresponding author; e-mail: cdewolf@mit.edu

Abstract
Whole life cycle emissions include not only *operational* carbon due to the use phase of the building, but also *embodied* carbon due to the rest of its lifecycle: material extraction, transport to the site, construction and demolition. The aim of this research is to extend the work on embodied carbon from the material scale to the structural scale. Therefore, a methodology has been developed to estimate the embodied carbon of an entire building structure based on the Structural Material Quantities (kg/m^2) and the Embodied Carbon Coefficients (kg$_{CO2e}$/kg). The collected data focuses mainly on structural materials, as more than half the material mass goes into the structure of buildings. The two main contributions of this paper are the quantification of embodied carbon in case studies and the comparison with a range of 260 existing buildings worldwide. The case studies are the rammed earth and tile vaulting applied in the Pines Calyx (United Kingdom) and the funicular vaulting and structural ribs applied in the HiLo Nest building (Switzerland). The case studies range between 100 and 200 kg$_{CO2e}$/m^2, more than two to four times lower than the average result obtained in collaboration with industry. In conclusion, this research offers a transparent methodology to evaluate the embodied carbon of different structural designs.

Keywords:
Embodied Carbon; Material Quantities; Global Warming Potential

1 INTRODUCTION

Life cycle energy in buildings includes operational energy for heating, cooling, hot water, ventilation, lighting on one hand and embodied energy for material supply, production, transport, construction and disassembly on the other. The synonymous terms "embodied carbon" and "Global Warming Potential" (GWP) describe all lifecycle greenhouse gas (GHG) emissions by their equivalent quantities of carbon dioxide (CO_2e). The other GHGs such as CH_4, N_2O, SF6, PFC and HFC can hence be converted to CO_2 using conversion factors in order to obtain a common unit for the environmental impact [1], i.e. the "carbon dioxide equivalent".

Many leading structural engineering and design firms are currently developing in-house embodied carbon estimators to answer the following question: what is the embodied carbon for different structures? A multitude of tools were developed in the last few decades to evaluate the environmental impact of the building sector. Life Cycle Assessment (LCA) tools can be used on the material scale and Material Flow Analysis (MFA) tools on the city scale. On the building scale, energy simulation tools only focus on operational energy. However, if the whole life cycle of the building is taken into account, it is important to look at the embodied energy as well.

This paper looks at embodied carbon rather than embodied energy, as this research aims to measure the contribution to climate change and quantifying specifically in carbon equivalent helps to compare the embodied with operational emissions. The same amount of embodied energy can emit different intensities of GHGs depending on the energy mix used and the carbon emitted or absorbed by the materials processed. For example, emissions occur in the

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chemical processing of cement, whereas carbon is sequestered in wood.

There is no consensus for embodied carbon assessment methods of buildings. Recent innovations have helped reduce the operational carbon, but a lack of benchmarking and literacy hinders the reduction of embodied carbon. Moreover, the Intergovernmental Panel on Climate Change [1] warns that carbon reduction is needed in the next decade if we want to avoid extreme climate catastrophes. With on-going population growth, and consequentially the increasing demand for buildings, reducing embodied carbon is imperative. Indeed, embodied carbon emissions are immediate and irreversible, unlike operational carbon, which can be minimised through energy efficiency measures. Furthermore, research in this field will help structural engineers and architects to understand how to lower embodied carbon and fill this gap in literature [2]. Finally, rating schemes such as LEED [3] and BREEAM [4] have begun including embodied carbon in their credit systems, though without defining baselines for benchmarking [5].

It should be noted that this paper is limited to structural material quantities. Cladding and other non-structural materials are not considered for three reasons. Firstly, this research aims to include structural engineers in the conversation about the environmental impact of buildings. Secondly, the structural components account for the greatest mass in buildings and contribute to roughly half of the total carbon emissions due to materials [6]. With a breakdown of embodied carbon for the different elements in offices, hospitals and schools, Kaethner and Burridge [7] demonstrate that the super- and substructure together represent more than 50% of the total embodied carbon emissions of buildings (Fig. 1). Thirdly, this helps to focus attention within well-defined parameters while still having a significant impact.

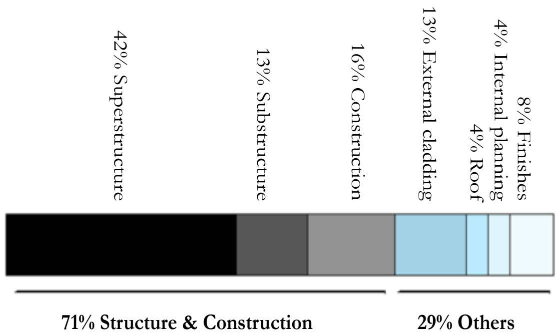

Fig. 1: Average breakdown in building elements of embodied carbon, after (Kaethner and Burridge, 2012).

2 PROBLEM STATEMENT

To develop a methodology for estimating embodied carbon on the building scale, two case studies are analysed: the Pines Calyx in St Margaret's Bay, Dover, United Kingdom, and the HiLo Nest project in Zurich, Switzerland. This work answers two key questions:

- What is the embodied carbon of low carbon structural designs?
- How do they compare to other building structures?

With the useable floor area as a functional unit, the GWP is measured in kg_{CO2e}/m^2. Two key variables are needed: Structural Material Quantities (SMQ), expressed in kg of material ($kg_{material}$ or kg_m) per functional unit (often m^2), and Embodied Carbon Coefficients (ECC), expressed in kg of CO_2 equivalent (kg_{CO2e}) per kg of material (kg_m). Presently, there is no clear standard for accurate ECC values and information on SMQ values for buildings is scarce.
As illustrated in equation 1, the GWP (kg_{CO2e}/m^2) is obtained by multiplying the two key variables: the material quantities in kg/m^2 with the ECCs, while taking waste or breakage into account. To calculate the total embodied carbon (total GWP), cradle-to-grave ECCs should be used. If we are only looking at the material embodied carbon (C_m), the cradle-to-gate ECCs can be used. These can be found in databases such as the Inventory of Carbon and Energy (ICE) database from the University of Bath.

$$GWP = \sum_{i=1}^{n} SMQ_i \left(1+\frac{w_i}{100}\right) ECC_i \quad (1)$$

where:

GWP Global Warming Potential (kg_{CO2e}/m^2)
SMQ_i Structural Material Quantities (kg_m/m^2)
w_i Waste (%)
ECC_i Embodied Carbon Coefficients (kg_{CO2e}/kg_m)

3 LITERATURE

Simonen [8] and Moncaster and Symons [9] highlight the general lack of data in the field of embodied carbon. Various reports have analysed the environmental impact of concrete [10, 11, 12], as well as the impact of cement [13]. Other articles describe the embodied energy of metals [14] and in particular steel [15, 16, 17,18]. Next to concrete and steel, the embodied energy of other construction materials such as timber has been discussed [19]. However, there is a significant variability in the ECC values for all materials.

The ICE report from the University of Bath summarizes ECC values for most construction materials [20]. The ICE report selects the best available embodied energy and carbon data. However, there is still a need for values for each

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country or region. The Carbon Working Group [6] also discusses the embodied carbon of common construction materials. They discuss the uncertainty of carbon footprints, data quality and variability. As different sources might not use the same assumptions, the Carbon Working Group identifies a need for a more reliable and comparable definition of ECC values. Several LCI and LCA tools exist to calculate impacts of single projects or materials. The commercial LCA software Gabi [21] and SimaPro [22] can perform an LCA of a unit of construction materials to estimate the ECC values. These commercial tools are common practice for LCA calculations, but their data are proprietary. Also, EcoInvent [23] provides thousands of LCI datasets for various applications from agriculture to electronics. OpenLCA [24] is a open source software that helps users perform LCA's of buildings.

The Athena Institute is a non-profit organization based in Canada that has integrated LCI data into building industry specific tools: the Athena Eco Calculator (free) and the Athena Impact Estimator [25]. Various companies have developed in-house tools focused on estimating the embodied carbon of their projects. Kieran Timberlake and PE International recently released the TALLY tool [26], which extracts data from Revit models. The SOM Environmental Analysis tool is a user-friendly embodied carbon calculator for design projects [27]. In the United Kingdom, the non-profit Waste Reduction Action Program (WRAP) developed a project-based database of embodied carbon [28]. WRAP asks users of the web-interface to clearly mark building life cycle stages and to reference the used LCA software, without asking specifically for material quantities. Many leading structural engineering firms have started an in-house database of structural material quantities or embodied carbon of their own projects. One thoroughly developed example is the Arup Project Embodied Carbon and Energy (PECD) mainly consisting of Arup buildings and projects from literature [29]. Although PECD contains approximately 600 projects, it does not yet allow the definition of a baseline due to the data scarcity and their wide ranges. Other companies such as Thornton Tomasetti have also developed a database of the material quantities, extracted via a Revit plug-in, and the embodied carbon of their projects.

This paper applies the available data on the ECCs of construction materials and SMQs in existing and newly developed databases in order to illustrate methodologies for lower embodied carbon buildings.

4 MATERIALS AND METHODS

4.1 Total embodied carbon

The total embodied carbon is the summation of the embodied carbon attributed to the production, construction, maintenance, and end-of-life stages. The first step of calculations (and often the main contribution to the embodied carbon) is for the production and construction stages. This is calculated in three parts: the embodied carbon of the materials themselves, the carbon emissions due to the transportation of the materials to the site and the carbon emitted during the building erection. The following equations are based on Vukotic et al. [30] and Moncaster and Symons [9].

There is no reliable database for cradle-to-grave ECCs, so that the calculation process described below is required. The overarching equation to calculate the total embodied carbon of the building is given by equation 2.

$$EC_{whole\ life} = \sum_{i=1}^{n} EC_{prod/constr,i} + \sum_{i=1}^{n} EC_{re,i} + EC_{eol} \quad (2)$$

where:

$\sum_{i=1}^{n} EC_{prod,i}$ is the embodied carbon of the product and construction process stage, including raw material supply, transport, manufacturing, the transport from manufacturer to the site, the construction-installation process;

$\sum_{i=1}^{n} EC_{re,i}$ is the embodied carbon of the use stages corresponding to repair, refurbishment and replacement;

EC_{eol} is the end-of-life stage embodied carbon, including de-construction/demolition, transport, waste processing and disposal.

4.2 Product and construction

The first term looks at the product and construction with equation 3.

$$\sum_{i=1}^{n} EC_{prod/constr,i} = \sum_{i=1}^{n} EC_{prod,i} + \sum_{i=1}^{n} EC_{transp,i} + EC_{constr} \quad (3)$$

where:

$\sum_{i=1}^{n} EC_{prod,i}$ is the material embodied carbon;

$\sum_{i=1}^{n} EC_{transp,i}$ are the carbon emissions due to transporting the material from the manufacturer to the site;

EC_{constr} is the carbon emitted during the building erection.

The first part of equation 3, the material embodied carbon, is calculated similar to equation 1, where the material quantities (kg) are multiplied with the cradle-to-gate ECCs, allowing to take waste or breakage into account.

$$\sum_{i=1}^{n} EC_{prod,i} = \sum_{i=1}^{n} SMQ_i \left(1 + \frac{w_i}{100}\right) ECC_{i,\ cradle\text{-}to\text{-}gate} \quad (4)$$

where:

SMQ_i are the Structural Material Quantities (kg_m);

w_i is the waste (%)

$ECC_{i,cradle\text{-}to\text{-}gate}$ are the cradle-to-gate Embodied Carbon Coefficients (kg_{CO2e}/kg_m)

The next part of the calculation looks at the material transportation and its carbon emissions. This is illustrated in equation 5, where for each

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material the number of truckloads is multiplied with twice the distance travelled from manufacturer to the site and with the fuel consumption in litre per kilometre as well as the fuel combustion emissions in kilograms of CO_2e per litre.

$$\sum_{i=1}^{n} EC_{transp,i} = \sum_{i=1}^{n} tl_i \times 2d_i \times fc_i \times fCO_{2i} \qquad (5)$$

where:
tl_i are the number of truck loads;
d_i is the distance from manufacturer to site (km);
fc_i is the fuel consumption (l/km);
$fCO2_i$ is the fuel combustion CO_2 emissions (kg_{CO2e}/l).

The third part looks at the carbon emitted during building erection (equation 6). The CO_2 emissions during construction and demolition of the building are obtained by summing over all materials the product of the equipment days on site, the fuel consumption per day and the fuel combustion CO2 emissions per litre of fuel consumed.

$$EC_{constr} = \sum_{i=1}^{n} ed_i \times fc_i \times fCO_{2i} \qquad (6)$$

where:
ed_i are the equipment days on site;
fc_i is the fuel consumption per day (l/day);
$fCO2_i$ are fuel combustion CO_2 emissions (kg_{CO2e}/l).

However, because we are comparing the structure only in this paper, we focused on the product life cycle stages (equation 4). Aiming at reducing the GHG emissions in the next decade to avoid extreme climate disruptions and focusing on structure, which generally does not require maintenance, this research prioritized the first life cycle stages in order to work with the two key variables SMQ and ECC.

5 RESULTS

5.1 Case Study 1: Pines Calyx

Helionix Designs is working on pilot projects that use rammed earth walls and tile vaulted roofs in order to create extremely low carbon buildings. One completed project is the Pines Calyx (Fig. 2) in St Margaret's Bay, Dover, United Kingdom.

The Pines Calyx is an event venue designed by Helionix Designs, in collaboration with Cameron Taylor and Conker Conservation, as an example of an extremely low-carbon building. The building illustrates how historical construction techniques can perform much better than contemporary buildings in terms of carbon emissions, energy needs and health. The client, The Bay Trust, and lead designer Alistair Gould of Helionix Designs wanted a carbon-neutral catalyst for rural and urban sustainable development. The design specified a lower carbon target than other sustainable projects had achieved, while still providing a high-quality, healthy environment. Rammed chalk walls, sourced from foundations excavations, and timbrel vaulted roofs largely replace traditional masonry and reinforced concrete.

Fig. 2: Pines Calyx.

5.2 Case Study 2: HiLo Nest building

The HiLo Nest project is a research and innovation centre planned as a penthouse guest apartment on the Empa Campus at ETH. The building will be illustrating lightweight concrete construction and adaptive building systems. The roof is an integrated thin shell and the floor system also uses thin vaulting.
The prefab integrated funicular vaulting system for the floors (Fig.3.a) is extremely lightweight, reducing the amount of concrete by 70%, when compared to traditional floor slabs.

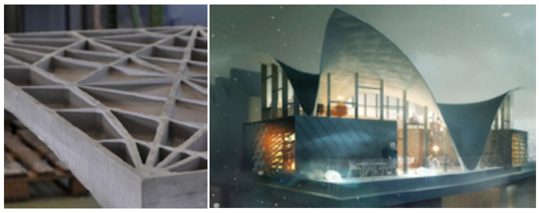

Fig. 3: a) funicular floor systems b) HiLo Nest project [31].

5.3 Comparison of the results

To calculate the GWP of the entire building structure, two key variables are used: the SMQs in kg/m^2 and the cradle-to-site ECCs in kg_{CO2e}/kg. The cradle-to-site ECCs are obtained by summing cradle-to-gate ECCs and gate-to-site ECCs (the carbon emitted for the transport and the construction of 1 kg of material). Then the total cradle-to-site ECCs can be multiplied with the material quantities to obtain the GWP.

The interactive Database for Embodied Quantity Outputs (DEQO) was created for this research. Architects, engineers and researchers can input their project and compare its material quantities and embodied carbon with hundreds of other existing building structures, worldwide. This methodology was applied to existing building structures obtained throughout the industry. The two low carbon case studies in this paper are compared against the cradle-to-gate average from over 260 existing building structures currently in DEQO. More detailed explanations and results about these 260 buildings can be found in [32, 33].

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The comparison of the results is shown in Fig. 4 and Fig. 5 (cradle-to-gate structure only). The Structural Material Quantities, normalized by the floor area (Fig. 4), demonstrate the material efficiency of the HiLo Nest building, due, mostly, to the innovative funicular floor system. Indeed, previous research demonstrated that the main contribution to the material quantities lies in the floor slabs.

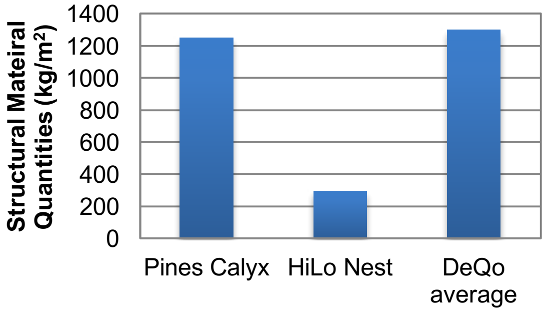

Fig. 4: Comparison of the material quantities.

However, when we translate this to the results for the GWP (Fig. 5), the influence of the material choices becomes clear. The Pines Calyx, using natural materials such as rammed chalk, has an environmental impact that is four times lower than the average building collected in the DeQo database.

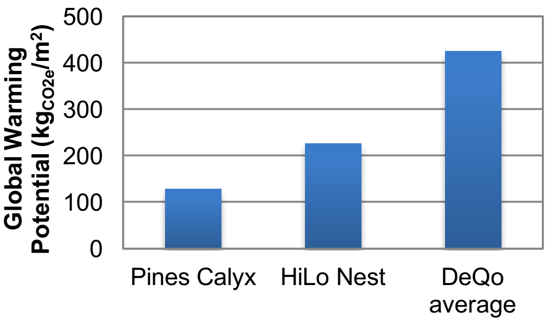

Fig. 5: Comparison of the embodied carbon.

6 DISCUSSION

These results demonstrate two main strategies to lower the embodied carbon of building structures:

(i) Improve the material efficiency
(ii) Choose low-carbon materials

The HiLo Nest Project focuses on reducing the material quantities with an innovative vaulted slab system, whereas the Pines Calyx restricts its environmental impact by using natural, local construction materials. The two strategies are not exclusive: low-carbon cement specification would further decrease the impact of the HiLo Nest system and the use of Timbrel vaults in the Pines Calyx minimised the use of concrete.

Note that the challenges in collecting accurate data for embodied carbon in building structures are twofold. Collecting the data on material volumes or mass requires a detailed Bill of Quantities from the contractor or an accurate Building Information Model from the designers. Estimating the most appropriate ECCs to calculate the GWP of the building structures relies on the material specifications as well as on the accessibility to databases such as ICE or EcoInvent and their accuracy.

7 CONCLUSIONS

In conclusion, we can now answer the two key questions:

(i) The embodied carbon of current low carbon design ranges between 100 and 200 kg_{CO2e}/m^2.
(ii) The case studies' embodied carbon is two to four times lower than typical buildings existing today.

The next steps are to gather more data-points and refine the accuracy of the data as well as to perform an uncertainty and sensitivity analysis. This research looks at carbon assessment as a part of standard LCA in order to define a baseline for benchmarks on the GWP of building structures. Upcoming steps are working with the Green Building Council and international standards to include these benchmarks in rating schemes and norms. Future research will expand to non-structural building products, in order to include the influence of maintenance and end-of-life impacts.

8 ACKNOWLEDGMENTS

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