The Institution of Structural Engineers

A short guide to embodied carbon in building structures

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Foreword

The first decade of the 21st Century was marked by the rapidly growing acceptance that the world's climate was changing, and the results of these changes would have a profoundly damaging impact on the environment and large numbers of people's lives. Generally agreement developed recognising the severity of the changes brought about by climate change would be relative to the ability of the world's populations to mitigate the causes of these changes and in adapting to a changing environment. A landmark agreement setting legally binding targets for carbon emissions by industrialised countries was signed by 174 countries in Kyoto in 1997, known as the Kyoto Protocol, these agreements came into force in 2005. The UK government published the Stern Report in 2006 which considered the economic impact of climate change on the UK. The report found that the costs of action far outweighed the costs of inaction. In the UK, November 2008 saw the Climate Change Bill enacted, with commitments to reduce by 80% of 1990 levels, carbon dioxide green house gas emissions within a period of 42 years. The world forum – COP15 held in Copenhagen in 2009 reinforced the depth of concern felt globally at the potential of climate change to impact on the planet and its peoples.

The Council of the Institution of Structural Engineers openly debated in October 2009, the contribution which structural engineering and specifically the Institution could make to the challenge of global climate change and the UK Government's commitment to reduce carbon dioxide emissions. The outcome from that debate was a request to the Trustees of the Institution to consider actions which could be taken which would empower structural engineers to make an effective contribution to reducing the impact of climate change.

This short guide is a direct result of the Trustees consideration of the Councils request. The publication was commissioned directly by the Trustees of the Institution of Structural Engineers from Professor Roger Plank, former Head of School of Architecture at Sheffield University and the then Senior Vice-President of the Institution.

In producing this guide the Trustees were mindful that the sustainability aspects of the built environment, best practice and legislative frameworks, differ across the international spectrum and that all were evolving very rapidly. The guidance contained in this publication should be considered as interim in this rapidly evolving field of knowledge and the Trustees contribution to furthering the necessary evolutions to our industry.

1 Aim and scope

1.1 Aim

This short guide is intended to provide structural engineers with practical advice on how they can contribute directly to reducing the embodied carbon/ energy footprint of the projects they design.

Many structural engineers have 'signed up' to the principles of sustainable construction, but are not sure what they can do practically, and may be frustrated because the structural engineer is not the natural leader for so many of the key issues – for example, the services engineer will normally lead on the design and specification of building environment systems (heating, cooling, ventilation) which are energy intensive, whilst the architect will generally be responsible for form, orientation, glazing, shading etc. Whilst the structural engineer should be aware of all of the relevant issues, most would be uncomfortable trying to take responsibility for these. The intention of this guide is to concentrate on just that part of the design which the structural engineer can directly influence, namely the embodied energy and carbon associated directly with the structure.

Of course, embodied energy and carbon should not be considered in isolation, and this guide will include reference to other relevant issues – notably operational energy – with some general comment about their relative importance and potential trade-offs. However, in many cases it is possible to make clear reductions in the embodied carbon without detriment to other measures of sustainability; this short guide will provide some guidance on this.

1.2 Scope

The guide is not intended to provide any of the following:
- A direct comparison of different materials and systems
- A comprehensive treatment of sustainable construction
- New data for the embodied carbon and energy of different materials and products
- A detailed commentary of life cycle assessment

The guide is short in length, therefore there is clearly no room to consider the broader issues of sustainability in any detail nor is it intended to provide new energy or carbon data for materials. The focus is on describing what information and tools are available and how these can be applied to estimate, and subsequently act as a vehicle to identify ways to reduce embodied carbon.

2 Introduction

There are a number of indicators and measures which need to be considered in a comprehensive treatment of sustainable development. Many of these are outside the direct influence of the structural engineer, but recently attention has become centred on global warming and climate change, and what is widely accepted as being one of the major contributors to this, namely the emission of carbon dioxide – often abbreviated simply to carbon – into the atmosphere. It should be noted that other gases such as methane, nitrous oxide and HFCs (hydrofluorocarbons) also contribute to global warming. In some circumstances, emissions of these other greenhouse gases can be significant, for example agricultural processes can often cause methane emissions (from animals or from soil), nitrous oxide is associated with the production of nylon, and HFCs may be used in the manufacture of some insulants. The global warming potential (GWP) of these gases is much more severe than carbon dioxide, but fortunately the corresponding quantities are very much lower. Where appropriate their effect on global warming is generally included in figures for embodied carbon, represented as a carbon dioxide equivalent.

Buildings have an extremely important role to play in the drive towards a low carbon economy. As an example, in 2009 it is estimated that the domestic sector accounted for 28% of UK energy demand, consuming 43.6 million tonnes of oil equivalent and causing 16% of UK CO_2 emissions; this corresponds to 75.3 million tonnes CO_2 equivalent[1]. Estimates vary, but it is generally agreed that between one third and a half of all carbon dioxide emissions are associated with building construction and operation in service as illustrated in Figure 1[2].

A building's carbon footprint describes its overall impact in terms of carbon dioxide emissions. Estimating the carbon footprint of a building needs consideration over its life cycle, including both what is termed the embodied carbon, which is associated with the construction of the building itself which would include the processing of materials, manufacture of products and components, and assembly on site, and the operational carbon, which is associated with the energy used to service the building, principally for heating, ventilation, cooling and lighting. Embodied carbon and how to quantify it, is the subject of this short guide.

If the structural design is to be informed by the need to reduce embodied carbon, it is important that some consideration is given very early in the design process to exploring potential reductions. During the initial design phases there is therefore a need to establish a quick estimate based on general information with little detail. In the context of structural design, the engineer's experience enables structural concepts to be developed to define form, layout, and the principal materials which will be used. Without the same experience of doing this for carbon emissions, structural engineers need quick and easy tools to perform relatively crude comparisons of ideas, and this guide provides some guidance on how to do this. Over time benchmark data will help establish rules of thumb for concept design.

As the design develops, more detailed carbon calculations are also required. At the later stages, the calculation of embodied carbon can require a large input of time and research into quantities and values for materials used. Whilst this may be of less value in refining the design concept, detailed issues such as material specification, particularly for concrete, can have a significant influence on the embodied carbon. A more detailed analysis of embodied carbon is also likely to become necessary as a means of certifying the carbon footprint of the building. Increased experience will, in time, help define how much detail will be required, and identify those aspects which are of greatest importance, and others which may have a negligible influence.

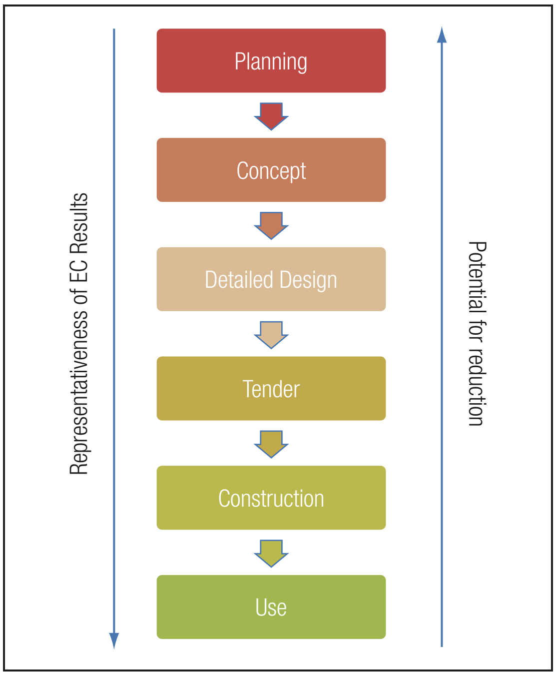

Figure 2 In order to achieve the best results it is important that embodied carbon estimates are undertaken early in the design process, although a significant contribution can be made at every stage

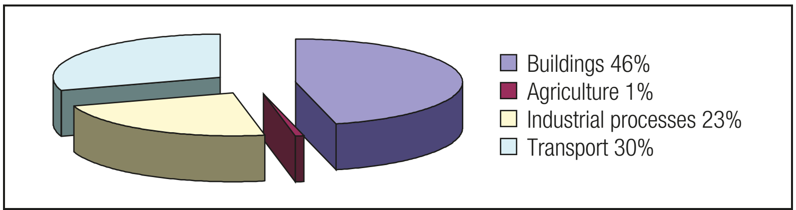

Figure 1 Sources of carbon dioxide emissions by sector

3 What is embodied carbon and embodied energy?

In the context of construction, embodied carbon (often abbreviated to EC or ECO_2) is a measure of the carbon dioxide emissions associated with creating the building fabric. It should therefore include the carbon emitted when sourcing and processing raw materials, that emitted to manufacture them into construction products, deliver them to site, and assemble them to form the building. Ideally it should also allow for any replacement or refurbishment during the building's life, and dismantling or demolition at the end of life and recycling. Of course this may be difficult to predict precisely so is often accounted for simply by including a percentage increase in the initial calculation. How an appropriate allowance should be made for such replacement and refurbishment is a central part of the work of the European CEN committee TC 350 which is developing a European standard for full building life cycle analysis. This will hopefully lead to greater clarity and consistency of treatment.

Embodied energy (EE) is the corresponding measure of energy used in these processes. The shift from energy to carbon as a unit to measure the embodied impact of a product or material is due to the growing importance attached to global warming and climate change. In many instances there is a close correlation between carbon and energy since a high proportion of man-made carbon emissions results from the burning of fossil fuels. This is particularly the case when considering the operational impact of a building. However, in some cases significant carbon emissions occur as a result of the chemistry of production for a particular process. The most obvious example for the construction sector is the production of cement which involves the conversion of calcium carbonate to calcium oxide, with carbon dioxide as a by-product. In such cases the total embodied carbon is the sum of that associated with the energy used in manufacture, and the carbon dioxide emitted as a result of the chemical reactions. This is illustrated in Table 1 which compares embodied energy and embodied carbon figures for the most common structural materials.

In addition, different energy sources, for example nuclear and fossil fuels, can have quite different carbon footprints, since carbon emissions are not necessarily directly proportional to energy consumption, and this is illustrated in Figure 3. The exact relationship depends on the energy source and DEFRA in the UK publishes relevant factors[4].

Table 1 Typical values for embodied energy and embodied carbon for common structural materials. (Source: University of Bath ICE v2.0[3])

Construction material	Embodied energy (MJ/kg)	Embodied carbon (kg CO_2/kg)
Cement	4.5	0.73
Steel	20.1	1.37
Brick	3.0	0.23
Timber	10.0	0.3

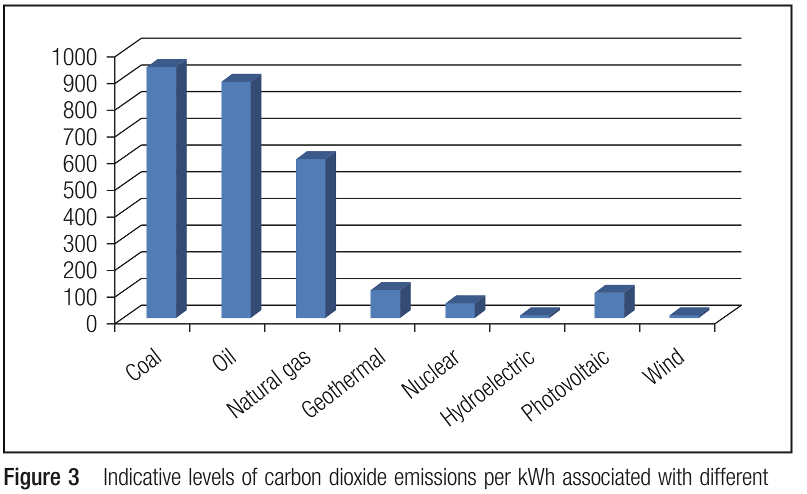

Figure 3 Indicative levels of carbon dioxide emissions per kWh associated with different energy sources

4 Data for embodied carbon and energy – life cycle inventories (LCIs)

The embodied carbon and energy for a basic material such as steel or cement can be determined by identifying all the relevant production processes including the extraction of raw materials, transportation and processing. For each single process step, the raw materials used, energy consumed etc. are quantified, and the corresponding impacts are determined. These are typically represented as MJ/kg and kg CO_2/kg for embodied energy and carbon respectively. Clearly there can be significant variations depending on the processes used by individual manufacturer/ suppliers, and the particular material specification – for example stainless steel or carbon steel, and glulaminated or sawn timber. In the case of concrete, individual data for the constituent aggregates, cement and water is combined. For building components such as a steel beam or reinforcing bar, additional processing needs to be included, and for components such as precast concrete units, data for different materials needs to be combined. In this way embodied carbon and energy data can be developed for the basic elements commonly used in construction. This data forms what is known as a Life Cycle Inventory (LCI) – a database for a range of materials and basic components, containing information such as the emissions of a variety of pollutants associated with the product – and this is an essential part of calculating embodied carbon.

When considering alternative structural systems, direct comparison of these figures is of course meaningless, because of the variation in load carrying capabilities of different materials – a steel beam for example will generally be much lighter than the equivalent reinforced concrete beam to perform the same function. It is therefore important to consider the total embodied energy/embodied carbon for the equivalent functional units rather than simply comparing these for the same quantity of different materials.

Data for an LCI requires detailed consideration of all relevant processes throughout every stage of the life of a product. This requires a quantitative environmental analysis of the product to measure a range of impacts, often including global warming potential, ozone layer depletion, eutrophication, and depletion of minerals and fossil fuels. It includes all the production processes and services associated with the product through its life cycle.

In order to quantify the different impacts a very detailed knowledge of the processes involved at the various stages of production, the energy (type and quantity) used and any chemical changes which may give rise to carbon dioxide is clearly required. Considerable reliance has therefore been placed on manufacturers to undertake this analysis or to engage life cycle assessment experts to do so, on their behalf, and provide the necessary data. This has been supplemented by independent studies, both to generate new data and check the validity of industry figures.

Precisely which stages of a product's life are included in LCI data sets can vary. This is what is referred to as the 'system boundaries'. Most data is quoted as 'cradle-to-gate' in which case it will include the carbon emissions associated with all stages from extraction through processing, but exclude any transportation to site and subsequent assembly. It will, however, generally allow for transport associated with the production process itself, so for example, in the case of concrete, the 'gate' is normally that of the ready-mix plant. Many carbon calculators combine figures for cradle-to-gate; this means that inevitable variations in the impacts associated with transport to site and disposal at the end of life are avoided; these should be considered separately, taking into account relevant information such as the specific project location.

Alternative boundaries are sometimes used including: 'cradle-to-grave' which includes all stages from extraction ('cradle'), manufacture, installation, and use through to disposal phase ('grave'); and 'cradle-to-cradle', which extends cradle-to-grave assessment to allow for recycling (see Figure 4). These boundaries are more often applied to products which do not have the complexity of a building or structure, and where the subsequent impacts are clearer (for example consumer goods or products such as, fridge/freezers or computers). What is important is that the system boundaries for the basic data are known, and that all other stages through the life cycle are considered, ensuring that there is no duplication or omission; although in some cases it may be reasonable to neglect a particular stage, or to use a simplified allowance, for example simply adding a percentage increase to account for transportation or site construction.

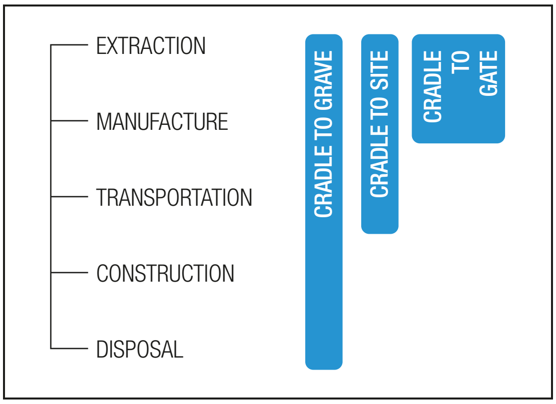

Figure 4 Schematic representation of different system boundaries

5 Quantifying embodied carbon

At its simplest level, the essential components required to quantify embodied carbon of a building are a database of individual material emissions (kgs. of carbon per kg of material) – as detailed in a Life Cycle Inventory (LCI) – and quantities of materials. The total embodied carbon is then the sum of all building quantities broken down by material, including an appropriate allowance for site waste, multiplied by their unit impact.

In principle the process is therefore very simple, and can be applied, for example, by entering total quantities into a spreadsheet containing embodied carbon data for all materials or products – the difficulty is assembling the embodied carbon data for each material. A number of organisations have developed LCIs based on the principles outlined above, and have made these available for more general use. This data may be presented for the basic materials and products of construction, but some sets of data are presented for components and systems. These might include, for example, a particular precast floor system accounting for concrete, steel and including the casting process, or a half brick masonry wall, accounting for both bricks and mortar. In such cases the data may be expressed in a way which is consistent with standard methods of measurement used for normal estimating, and using appropriate units such as kgs. of carbon dioxide per sq. m.

6 Sources of data

There are only a few such inventories providing sources of this material data and some of these are not readily available because they form part of comprehensive life cycle assessment software, or are for internal use within a particular organisation.

One impartial, open and freely available inventory is the Inventory of Carbon and Energy (ICE) developed by the University of Bath[3, 5]. This contains cradle to gate data for both embodied energy and carbon and has been largely assembled from published information and life cycle assessments provided by a variety of sources. The data presented is a synthesis of a much broader range of data collected by the authors; with individual entries based on a number of different studies for each material. Inevitably data for the same material from different sources showed some variation – partly as a result of variations in LCA methodologies, but more particularly because of even larger differences in production methods. The authors have therefore had to use their expert judgement to present explicit values rather than a data range, but the results are consistent with other databases. The authors also acknowledge that the embodied carbon data has often had to be calculated based on published information on energy and this may therefore compromise accuracy a little. Despite these reservations the ICE database is generally recognised as providing good quality data for the UK, and it is freely available in a suitable format. It is therefore widely used, and a number of organisations have used it as the basis for developing their own tools for estimating embodied carbon, but as with any database, its limitations should be understood. The inventory appears to be actively updated with revisions appearing roughly every year, so users should ensure they have the latest version. A brief extract of the ICE database is shown in Table 1. However, it should be noted that the database provides a considerable degree of refinement, for example quoting different data for particular concrete strengths and specifications.

Some companies have published their own inventories, sometimes based on the ICE, but refining the data to suit their own applications.

As an example, Mott MacDonald has used the ICE, supplementing it with independent data which they have sourced themselves and information from manufacturers, to create a database of carbon dioxide emissions for all activities of construction work. This is included alongside unit prices in the latest edition of the annual price book which they prepare[6].The information is related to standard methods of measurement for estimating material quantities. Individual material impacts have therefore had to be processed and combined as necessary to provide data for standard elements of construction. All base data is cradle-to-gate, so transportation to site and other downstream impacts are ignored, but appropriate plant on site is included. As with the University of Bath database, where the authors had a range of data for a particular product, they used some judgement and presented a single figure. All data can be modified by the user if particular circumstances suggest a different value should be used, and new information can be added, giving both flexibility and transparency. A similar combination of economic and carbon data for every material and unit of work is included in The Institution of Civil Engineer's latest edition of its Civil Engineering Standard Method of Measurement – CESMM3 Carbon & Price Book[7].

Arup has adopted a similar approach, and has also included figures relevant to product suppliers outside the UK. Although this data is not published in full as a separate inventory, it is integrated into the commercially available Oasys structural software[8]. The data includes more precise figures for different concrete specifications which Arup has used in whole building studies in collaboration with the Concrete Centre[8–10]. These studies showed just how much variation there can be in calculations for embodied carbon as a result of variations in both material specification and methodology as illustrated in Figure 5. This led naturally to the conclusion that it is important for engineers to consider the detailed specification of concrete rather than using generic figures for the material, with reductions as high as 200kg CO_2/m^2 achieved in extreme cases.

BRE has derived independent embodied carbon figures for structural and architectural components, rather than basic materials and these are published in the Green Guide to Specification[11]. The information is categorised by building element or system, and uses a letter grading to represent the combination of thirteen different environmental impacts, including embodied carbon. The latest edition (4th, pub. 2009) of the guide does include absolute values of embodied carbon per functional unit (typically one square metre of floor or wall) of different systems, but

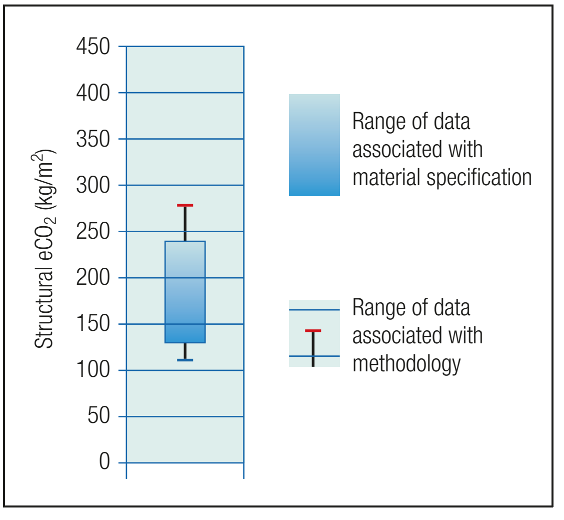

Figure 5 Variations in the embodied carbon of the structure of a whole reinforced concrete framed building, principally as a result of differences in concrete specification (Courtesy of Arup). (The methodology for accounting for recyclability of steel and the variations in manufacturing methods used is discussed in Section 7)

as yet does not explicitly include similar data for basic structural materials such as steel and concrete.

Other databases provide similar information for some locations outside the UK. These include ELCD, the European Reference Life Cycle Database, from the European Commission[12], and US LCI database[13]. Both are freely available, and are likely to grow into valuable resources in the future.

Commercial Life Cycle Assessment packages such as Athena (North America), GaBi (Germany), SimaPro, and RMIT (Australia)[14–17] also include comprehensive LCI data. However the use of such packages is a rather specialist area and they are unlikely to be of practical use for design engineers on a routine basis.

A number of engineering organisations such as Arup, Atkins, Buro Happold, Expedition, Jacobs and Ramboll have used the ICE, as a basis for developing specific tools for calculating embodied carbon and energy. They generally adopt a simple spreadsheet approach, applying the database to a set of quantities, enabling a quick and easy estimate of embodied carbon to be determined. In many cases these tools are for internal use within the organisation, but some are more widely available, for example Arup's Oasys structural software[8]. Jacobs has developed the Environment Agency Carbon Calculator[18] for calculating embodied carbon (along with transport and site carbon) for the Environment Agency's flood defence schemes, and Mott MacDonald markets a calculation tool[19] using its Blackbook data. A further tool is the Construction Carbon Calculator[20]. This is freely available on the internet and provides a very simple calculator giving an approximate estimate of embodied carbon. It appears to be based on data for North America, although the values used for individual items are not visible and cannot be changed. There is currently insufficient detail to enable a full design evaluation.

A more extensive list of tools is included on the Wiki available on the University of Bath ICE website[21].

7 Critical assessment of data

There are a number of aspects which can affect the quality and value of the data presented in a life cycle inventory (LCI). These include transparency and variability. The data should also be in meaningful units rather than based on a grading system. There are some issues such as how to allow for recycled materials, carbon sequestration, and carbonation of concrete, which are the subject of ongoing debate, and for which at present there is no clear consensus. In such cases it is very important to know the basis on which the LCI data has been determined, for example whether adjustments have been made to allow for recycling (this is particularly important in the case of metals), or what material specification has been assumed (for example in the case of concrete).

7.1 Transparency

It is important that the LCI data is visible to the user, and ideally can be modified to accommodate any additional information which may be available, or more specific data which may be applicable in a particular instance. The system boundaries should be specified. It is normal for figures to be given on the basis of a cradle-to-gate analysis, but often with some adjustment to allow for recycling at the end of life for highly recycled materials such as metals; this allows additional impacts such as transportation and site assembly to be included as appropriate for the particular project. Without this transparency it is too easy for inappropriate data to be used, or worse, for parties with a vested interest to incorporate values which are favourable to themselves.

7.2 Differentiation

Data needs to be sufficiently detailed to enable differentiation between similar products. For example a generic figure for timber is inadequate because it does not show the differences between for example, softwood, plywood and glulaminated timber products. As the Arup study has shown[9] and is evident from the ICE database[3], the figures for concrete need to reflect cement content and strength, and both post tensioned and precast concrete should be treated separately from normal reinforced concrete elements. Furthermore the use of cement replacements such as pulverised fuel ash (PFA) and ground granulated blast furnace slag (GGBS) can have a very significant effect in reducing the embodied carbon for concrete.

7.3 Currency

Data can quickly become out of date because of continual improvements in processes. Its validity should therefore always be questioned and clearly it is important to have current data. Generally in the UK, trade organisations and bodies representing different material producers recognise the importance of this and are increasingly providing good quality information into the public domain. The intention of the European committee CEN/TC 350 is to provide a formal mechanism for doing this in a regulated way.

7.4 Variability

A major issue with LCI data is the inevitable variability, for example in the mix of constituent materials forming generic products. This can, in part, be addressed by a more detailed database, such as the inclusion of data for concrete related to specification.

Different suppliers may have quite different processes, and these can result in very significant variations. For example different processes for steel production can use quite varying amounts of energy and a greater amount of energy is needed for wet-kiln than dry-kiln cement production. This is generally implicitly allowed for because most data reported in LCIs for a particular country reflects the proportion of the different processes used in that region. Of course this proportion can clearly change significantly with time, reinforcing the need to maintain data to ensure currency.

A further source of variability is the different life cycle assessment methodologies which may be used to obtain embodied impacts, and different databases can therefore contain quite different values for what is nominally the same product. Whilst such assessment methods are covered by various standards such as PAS 2050[22] and ISO 14040[23], some of these allow a wide range of interpretation. A series of European standards is currently being developed by CEN/TC 350 for the sustainability assessment of ‘construction works’, including environmental performance. This is likely to have a major influence in construction, superseding current standards and providing a clear definition of how environmental profiles should be determined for building materials and products.

There are potentially significant variations in the data applicable to different countries, and in some cases, notably China, India and the Middle East, there is little or no information available. LCI data for Europe is reasonably accessible, although it may be embedded within commercial LCA software.

Recognising these variations, it is clear that this is not an exact science and the base data is changing over time. It may therefore be appropriate for all tools and reports to include an indication of the confidence levels in the accuracy of the results, perhaps using ‘error’ or variability bars.

7.5 Energy sources

LCI data should be based on primary energy; that is, the energy contained naturally in raw fuels without any conversion or transformation, rather than delivered energy, most commonly electricity. In this way the inefficiency and losses in transmission, which can be significant, are automatically included. The source of primary energy used in a particular process can itself have a significant effect on the amount of resulting carbon emissions. For example energy from fossil fuels generates significant carbon dioxide emissions, but wind and solar energy produce very little.

7.6 Transport and site work

As discussed, LCI data is generally presented on the basis of a 'cradle-to-gate' systems boundary. Clearly there are additional impacts (i.e. increased energy use and carbon emissions) associated with transportation to site and site installation. The UK Government has published data for transport[24, 25] enabling these impacts to be estimated based on typical travel distances and the mode of transport, and the Arup/Concrete Centre[9] study includes further details illustrating how this might be adapted and applied in practice. Of course detailed information may not be known until a specific supplier has been engaged, making it difficult to make a suitable allowance during initial design. However, studies by a number of organisations have shown that for most materials the additional embodied carbon associated with transport to site is relatively small (<10%). The exception is aggregates for general use. In this case the embodied carbon data for extraction and processing (cradle-to-gate) is so small that the effects of transport to site are much more important than for other materials. It may also be an important consideration for precast concrete, but for other materials it can normally be accounted for approximately by a general allowance of 5–10%.

Clearly for materials sourced from outside the UK, or where very long travel distances by road are involved, impacts due to transport may also be higher and need to be considered.

The embodied carbon associated with site works is also generally small compared with the cradle-to-gate figures. A small percentage may be added for construction, but again this is often ignored except in special cases such as the construction of deep basements which may involve significant site activity and transportation, but use small quantities of materials.

It should be recognised that some components are likely to need replacing during the life of the building. Whilst this may not normally be relevant for the structure itself, some components such as cladding may be the responsibility of the structural engineer, and an allowance should be made for the additional impacts associated with replacement or refurbishment.

7.7 Allowance for recycling

How recycling is accounted for is a complex and contentious issue. The system boundaries for most LCI databases are cradle-to-gate. Ideally a thorough treatment of embodied energy/embodied carbon should consider the full lifecycle of the building or structure, including end of life. As discussed above, the impacts associated with delivery and construction can be included. Impacts can also be introduced for demolition/dismantling and disposal, which, like transportation and site work, are generally small. However, for some materials and products there may be possible benefits as a result of recycling or reuse, and for certain materials, notably metals, these can be significant.

A number of studies[9, 26] have been conducted in an attempt to provide a rigorous and logical method of allowing for recycling, however although alternative approaches have been developed, none has been formally accepted. Most commonly, recycled content is reflected in the embodied figures through reductions in virgin material and processing energy for creating the final product – this is the recycled content approach. The recycled content approach reflects well the impact to produce a material. For specific products, some inventories cite impacts based on what recycled content *can* be achieved (often called 'recyclability') – this is the substitution method (closed loop system expansion). The substitution method suggests how much benefit there is from the end of life recyclability. These two methods cannot be used together because it would double count the benefit of recycling. However, neither approach deals adequately with all aspects of the problem, and the so-called 50 : 50 method has been developed to share the benefits of recycling between the initial and subsequent uses. Each approach has its advantages and disadvantages. These three approaches are summarised by the authors of the ICE, and they state that regardless of the method chosen it should be consistent with the goal and scope of study and that the method and results should be transparently displayed.

7.8 Allowance for use of waste materials and by-products

A number of construction products make use of waste materials or by-products. For example blast furnace slag, a by-product of steel manufacturing, can be used as a cement replacement in the production of concrete. The question therefore arises as to how the embodied energy/embodied carbon associated with the waste product should be allocated between two products (in this example, steel and blast furnace slag). An approach sometimes adopted in a life cycle analysis is to do this on the basis of economic value, although boundary standards also generally allow other methods of allocation based on mass or volume. In the case of blast furnace slag, using allocation by value, the carbon emissions associated with a quantity of steel, and coincidentally an associated quantity of blast furnace slag, are divided between the steel and slag in relation to their monetary value.

In practice the effects of waste products on the overall embodied energy values for steel and concrete are likely to be relatively small, but the replacement of cement, with its high embodied carbon, by blast furnace slag (GBFS) or pulverised fuel ash (PFA) – a waste product of coal fired power stations, can have a significant effect in reducing the embodied carbon of concrete.

7.9 Allowance for materials wasted on site

Standard data is available from the Waste and Resources Action Programme (WRAP)[27] for typical wastage rates categorised by material and expressed as a percentage. Waste should generally be accounted for by increasing the basic material quantities by the corresponding waste percentage. Thus:

$$\text{EC total} = \text{EC}_{\text{unit}} \times \text{W}(1 + \text{WR}/100)$$

where:

EC_{unit}	is the unit value of embodied carbon for the material from the LCI (kg CO_2/kg)
W	is the weight of material from Bill of Quantities (kg)
WR	is the % allowance for waste for that material

7.10 Treatment of sequestered carbon

Some materials, notably timber, absorb carbon dioxide, during growth. This is locked into the timber when it is harvested, and it is only released at the end of life when the timber is burned or as methane when it is composted. The process whereby the timber removes carbon dioxide from the atmosphere is known as carbon sequestration. Some have argued that LCI data should therefore make an allowance for this sequestered carbon, in which case the embodied energy for timber would often be negative. The ICE database consciously excludes sequestration on the basis of it being a cradle to gate study, but PAS 2050 includes a simplified approach. Until this issue has been resolved, some engineers quote values of embodied carbon for timber based on both the inclusion and exclusion of carbon sequestration.

7.11 Carbonation

Part of the carbon dioxide emitted during cement production will be absorbed back into the material via a process known as carbonation. In theory this can be up to 90% for pure lime products, although excessive carbonation in reinforced concrete can lead to problems of durability. For typical concrete construction the figure is nearer to 10–15% and the process is very slow. In concrete structures it is restricted to a thin surface layer, but if the concrete is crushed at the end of life, carbonation rates can increase significantly, thereby offsetting some of the carbon dioxide emissions during manufacture. However, if exposure is restricted, for example by using the crushed concrete as fill, the process can be severely affected, and as a consequence many practitioners do not make any allowance for carbonation.

8 Some practical issues

The principles of carbon accounting can be applied simply to determine the approximate amounts of embodied energy/embodied carbon of a building structure. How the results might be used in practice to influence design decisions is less straightforward, as other factors need to be considered, even in the context of sustainable construction, the most significant of these is the efficiency of the building with regard to operational carbon and energy.

It is also important to develop some perspective of what might be considered reasonable benchmarks to avoid unrealistic targets. This section therefore discusses some practical issues surrounding how the results of embodied carbon calculations might be applied in real projects.

8.1 The relative importance of embodied carbon

The carbon footprint of a building should include all carbon emissions, embodied and incurred by its operation. Therefore to produce a reasonable assessment of this carbon footprint consideration will need to be given to the full life cycle of the building. The relative importance of embodied carbon to the emissions associated with the operation depends on many factors, notably, the design life of the building, its energy efficiency, the use of renewable energy, and the intensity of the servicing.

For typical commercial buildings the proportion (embodied carbon : operational carbon) has been estimated at between 1 : 5 and 1 : 10, depending on design life and specification[28, 29]. As buildings become more energy efficient and use more renewable energy particularly site generated, for example by photovoltaic cells, this ratio is likely to reduce, increasing the relative importance of embodied carbon. This conclusion is supported by a recent report – 'Redefining Zero'[30], which suggests that the embodied carbon of some types of building may account for more than 50% of their total whole-life emissions. When embodied carbon becomes a significant proportion of the carbon footprint of a building, the supporting structure being a 'high mass' component, will be a significant portion of the total embodied energy/embodied carbon of the whole building fabric (which will include contributions from elements such as the envelope and internal finishes), so the importance of the structural engineer's design and specification increases further.

Whilst the structural engineer may have little direct influence over the operational carbon and energy, the importance of these impacts should not be ignored, and it is essential to maintain a holistic view of the design. It would be counterproductive to minimise embodied carbon if this were offset by an equal or greater increase in operational emissions. Ideally the two should be considered together, but the calculations for operational carbon will require a different approach. At its simplest these might be, for example, typical figures for construction that achieve the minimum performance specified in national regulations, using published energy benchmarks, or by using hand calculations. More precise figures will require some environmental modelling to predict energy usage over the expected design life of the building.

A number of software tools have been developed specifically for the environmental impact assessment of buildings – for example, BREEAM[31] and LEED[32]. Both these tools include for elements of operational and embodied carbon, along with a range of other indicators, to give an overall rating for a building throughout its design life, but do not provide specific data for embodied carbon.

Commercial life cycle assessment software packages such as GaBi and SimaPro may be of interest to the specialist, but are not intended for routine design work and require expert use. They do however provide a potentially rich source of data for basic materials and products which can then be incorporated into simpler design assessments.

8.2 Baselines

At present there is insufficient experience available to establish good benchmarks on which to compare buildings/structural techniques. Consequently the process of calculating embodied carbon can only be used to compare options. However as experience grows, and more data become available, it is likely that it will be possible to identify typical figures for embodied carbon and establish baseline data. Some companies are working towards doing this by back calculating the embodied carbon for a number of

Olympic Velodrome, London. Image courtesy of London 2012. During the design of the velodrome, an investigation into options for the roof structure was undertaken by Expedition in collaboration with the architects Hopkins. Four different options for the distinct double curved roof were evaluated on cost, carbon, risk and programme impact. The steel cable net roof (Option C), was shown to have the lowest embodied carbon and also performed well on cost and programme, and it was this solution that was taken forward to construction. The lightweight design of the Velodrome means that it has a very low embodied carbon for the scale of structure and building typology.

completed buildings. This also helps reveal those building elements which contribute most to embodied carbon.

Ideally such a benchmarking exercise will be undertaken by a number of companies, using a consistent methodology and reported in a transparent, accessible way, so that the outcomes can be shared with the profession. In the absence of such benchmarks, consulting engineers Jacobs has adopted an approach for its in-house assessment tool which determines a baseline through the selection of 'typical constructions' for each of the major building elements (foundations, external walls, roof, etc.) for a project. For the external envelope, the 'typical constructions' available comply with the limiting U-value standards specified in the Building Regulations Approved Document Part L.

8.3 Waste

The net embodied carbon of a building can be improved by avoiding over-specification of materials and reducing waste. This requires careful design and planning, but is no more than the good practice which should be adopted on any project. Studies indicate that most waste arisings result from the fitting out of a building rather than structure, and both the BRE SMART Waste program[33] and WRAP[27] provide useful waste benchmarking data, for example; typical quantities of each material (by weight) generated as waste for each unit area of construction type.

Some notable projects such as Heathrow Airport Terminal 5, and the London 2012 Olympic Park Main Stadium have demonstrated what can be achieved in reducing waste and re-using materials, thereby contributing effectively to a reduction in the carbon footprint.

8.4 Experience

Experience of calculating embodied energy/carbon for buildings is at present limited, although some independent studies[34] have been conducted, particularly comparing the performance of different structural systems. Preliminary indications are that in general there is relatively little variation in embodied energy/embodied carbon for different forms of structure using the same basic structural grid, particularly when regard is taken of the uncertainties and variations in data for nominally the same materials. However, varying the structural layout itself can have a significant beneficial effect, as can the detailed design and specification, for example of the concrete mix. Design forms which are relatively inefficient, very material intensive and/or use components with high embodied energy values will naturally result in higher embodied carbon however this has not been found to correlate with absolute weight or cost when comparing between different material. Long span and some specific types of floor construction such as flat slab and slim deck use more material than some other types of floor construction and hence will probably have a higher carbon footprint than other systems.

It is very important that embodied energy/embodied carbon is considered in the context of the overall design – as an example, longer spans have become popular because they enable more efficient use of floor space, and hence this could potentially increase the design life of a building by improving its flexibility, and as a result the effective carbon footprint is reduced.

8.5 Scope – what to include

Ideally, an embodied energy /embodied carbon assessment should include all major elements of the building. Considering just the structure – which might typically account for between 15% and 50% of the total embodied energy for the building[35], can distort the picture because of potential interactions and effects on other elements of the building. For example, deeper floor construction will call for increased cladding, fair faced concrete can eliminate the need for finishes, and some design layouts may lend themselves to reductions in applied fire protection to the structure. Ideally the process should therefore involve the entire design team, although as the structure is a key aspect, structural engineers could play the lead role, applying the same principles outlined here to other elements of the building fabric.

9 Conclusions

Calculating embodied carbon is in principle a simple process, requiring a comprehensive set of data (the LCI) and a breakdown of quantities. LCI data is available, with new sources appearing and existing data being refreshed. Whilst at present there can, in some cases, be considerable variation in the data for nominally the same basic material, this situation is likely to improve as more data becomes available, and consistent methodologies are agreed. So there are no obstacles in principle to the structural engineer undertaking these calculations. At present there is no requirement to determine a building's carbon footprint, and little benchmark data to use as a basis for comparison. However, with a UK Government commitment to a reduction of 80% of carbon dioxide emissions from 1990 levels by 2050, this is likely to change in the near future. This presents an opportunity for structural engineers to assume responsibility for a central role in achieving low carbon building construction by minimising the associated embodied carbon.

This may start by just calculating the embodied carbon of structures in the simplest way possible. With a little time, the experience gained might then lead to an improved understanding of how initial design decisions can influence the embodied carbon, and the data generated can help to establish reasonable benchmarks, particularly if these are shared across the structural engineering community.

Embodied carbon is just one aspect of sustainable construction; it is that which the structural engineer can most directly influence, but it is important to take a holistic approach recognising that in some cases design decisions to minimise embodied carbon could result in increasing other impacts. However, there are likely to be a number of aspects of the structure which can be controlled without any adverse effects on other measures of sustainability.

Bryghusprojektet, Copenhagen. Image courtesy of OMA. Arup carried out embodied carbon calculations as part of a broad response to the client's sustainability objectives. The team used those calculations to set a carbon target for the next stage of the design. This approach has ensured that the significant elements for this particular project have been identified and can now be targeted.

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Appendix A – Worked examples

This Appendix includes two simple examples to illustrate how the approach outlined in this short guide may be used in practice.

The first example is for a unit area of a typical cavity wall; the second is for a fictitious building including elements of steel, concrete and timber construction, and using assumed quantities which in practice would need to be estimated or taken directly from the Bill of Quantities.

Example 1: Cavity wall construction

The quantities (kg) of materials required for the construction of 1m^2 of a standard cavity wall are shown in Table 2, together with the unit values for the embodied carbon for each material taken from the ICE database[3]. The contribution from each component is simply the product of the respective values, and the total embodied carbon is the sum of these values as shown.

These quantities are based on specified requirements and some allowance for waste on site should normally be included. The WRAP Net Waste tool[27] gives 'typical' and 'good' figures which can be used to amplify the figures as appropriate. These are shown in the two right hand columns.

Clearly this unit value of embodied carbon per m^2 of wall can then be used as a convenient way of estimating the total embodied carbon for a specified wall of given length and height, using the same construction.

Example 2: A hybrid structure, with some areas framed in reinforced concrete, some using steel framing with composite floors, and some use of structural timber

In the early stages of design, the quantities (tonnes) of materials can be estimated; towards the end of the more detailed design stage, more precise information may be available through the bill of quantities. Assumed quantities for concrete, structural steel, rebar, decking, and structural timber are shown in Table 3 together with the unit values for the embodied carbon for each material, taken from the ICE database. As in the previous example, the contribution from each material is simply the product of the respective values, and the total embodied carbon is the sum of these values as shown.

It is clear that there is a great deal of uncertainty surrounding much of the data used in the calculations for embodied carbon, and it is important that engineers recognise this. The results should be

Table 2 Example of calculating embodied carbon for a unit area of cavity wall

Material	Quantity (kgs)	Unit embodied carbon (kg CO_2/kg)	Embodied carbon (kg)	Typical wastage[27]	Adjusted embodied carbon
Bricks[a]	120	0.23	27.6	20%	33.1
Blocks[b]	180	0.059	10.6	20%	12.7
Mortar[c]	30	0.163	4.9	5%	5.2
Insulation[d]	1.2	1.05	1.3	15%	1.5
Plaster[e]	14	0.12	1.7	5%	1.8
Total			46.1		54.3

Notes:

[a]The manufacture of clay products, including bricks, release carbon dioxide emissions, depending on the type of product. The figure used here is for general clay bricks, for which there is a very large data range.

[b]The embodied carbon for concrete blocks is largely dependent on the specification of the concrete mix used. The figures quoted in the ICE database are estimated from assumed concrete block mix proportions, plus an allowance for curing, plant operations and transport of materials to factory gate. The value used in this case is for concrete blocks with a strength of 8N/mm^2.

[c]The figure used is for a 1 : 1 : 6 (cement : lime : sand) mix, which assumes a typical cement. The data for mortar covers a wide range as it is highly dependent upon the clinker content of cement, manufacturing technology and the possible use of additions or replacements, such as fly ash, slag . . . etc. Cement is an important building material and is important in the manufacture of concrete.

[d]The ICE reports that data for insulation generally is poor with a considerable variation (±40%). The figure used here is for rockwool, for which there is good data available.

[e]The ICE notes that there is little good quality data available for plaster, particularly for embodied carbon. The figure used here is for general plaster

No allowance has been made for transportation, but this can be included by using published unit data[4] with estimated total journey distances and mode of transport.

Table 3 Example of calculating embodied carbon for a whole structure

Material	Quantity (t)	Unit EC (kg CO_2/t)	EC (t)
Concrete[a]	2737	153	418
Steel[b]	128	1420	182
Rebar[c]	163	1310	214
Decking[d]	15	1450	22
Timber[e]	32	190	6
Total			842

Notes:

[a]The figure used is for concrete strength R32/40 using no cement replacements. The embodied carbon is directly related to strength, with figures quoted in ICE ranging from 124kgs CO_2/t for R20/25 (even lower for weaker mixes) to 176 for R40/50 (and more for stronger mixes). The variation can be even bigger in practice because of differences in cement content for the same design strength. The use of cement replacements has an even more dramatic effect. Using 30% GGBS in place of cement reduces the unit EC value from 153 to 125 and 50% replacement reduces this further to 94. This clearly demonstrates the importance of careful specification of the concrete in minimising EC, although it is important to ensure that the proportion of cement replacement is suitable for the particular application.

[b]The figure used is that quoted for Sections, using the data listed for 'UK Typical – EU 59% recycled'. Other figures are included in the ICE database are for the 'Rest of the World typical – 35% recycled', 'World typical – 39% recycled', and 'Primary' (0% recycled). The corresponding data for embodied carbon is listed as 2010, 1930, and 2880kg CO_2/kg. The proportion of recycled feedstock has a very significant influence on the unit EC. The ICE does not include a figure for 100% recycled content, but this is typically quoted as about 430kgs CO_2/t.

Unlike concrete, it is acknowledged that specifying the precise constituent materials or production route for steel is not appropriate. This is partly because of the high recycling rates and fact that some production of steel from raw materials is necessary to satisfy demand as well as to provide a source of material for subsequent production through recycling. How this is allowed for is a complex issue, and is discussed in some detail by Hammond and Jones[3] in Annex B to the ICE database.

[c]The figures used are for 'UK typical', and similar comments apply as for structural steel above. However it should be noted that UK manufacture of rebar uses 100% scrap feedstock.

[d]The figures used are for galvanised coil (UK typical), and similar comments apply as for structural steel above. However, as can be seen from this example, the contribution of decking to the overall EC for the structure is relatively small, so the overall results are not sensitive to the data used.

[e]The figures are for sawn softwood, and exclude the element from biomass energy. The ICE does not include an allowance for sequestration. There is little good quality data for timber in the UK and EU, although there is better information for the USA. However, the data should be considered as region specific, so is not applicable elsewhere. There are often significant variations in the energy used in the manufacture of timber products. Moreover, the fuel mix may include timber off-cuts. This is allowed for in the ICE by separating the contributions of this biomass fuel from that of fossil fuel. If the timber is from a sustainably managed source the embodied carbon from the biomass fuel may be ignored.

interpreted accordingly, and although they do not provide precise information, used sensibly they can help inform design decisions. In doing so engineers should consider the 'range of uncertainty' which can to some extent be quantified by using upper and lower bound values for the basic data. The figures will also help identify those elements which contribute most to the total embodied carbon, and those which are relatively unimportant, allowing attention to be focused on making reductions where they will have most effect.

Further examples

A number of examples and case studies have been published, illustrating the process of calculating embodied carbon, and how the results may be used to inform the design[5, 10, 30, 34, 35].

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