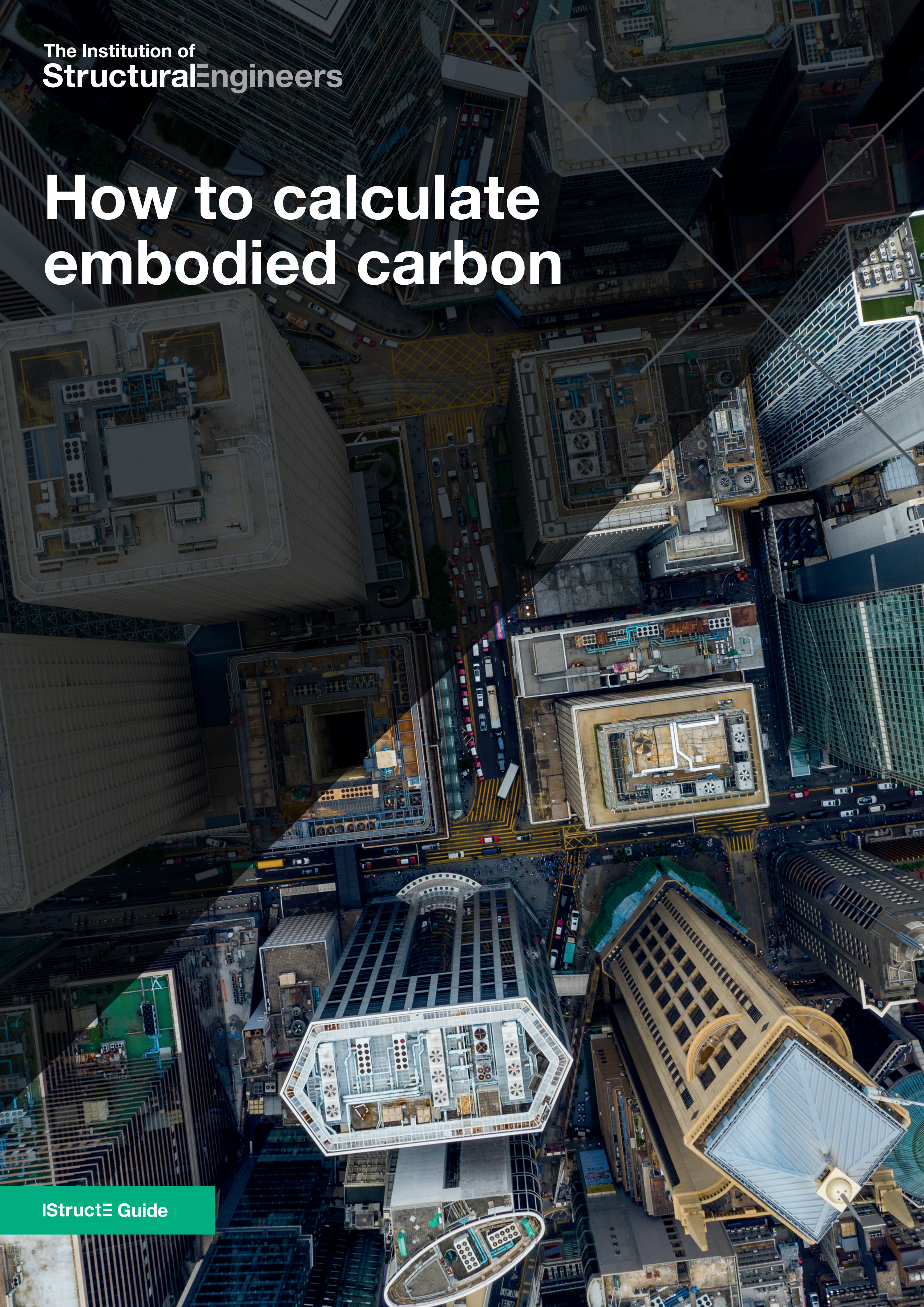
The Institution of StructuralEngineers

How to calculate embodied carbon



IStructE Guide

The Institution of
StructuralEngineers

How to calculate embodied carbon

Authors

O P Gibbons	MEng (Arup)
J J Orr	MEng(Hons) PhD CEng MIStructE FHEA (University of Cambridge)

Reviewers

W Arnold	MEng(Hons) CEng MIStructE (Arup + The Institution of Structural Engineers)
S Boote	BEng(Hons) CEng MIStructE AMICE (Webb Yates Engineers)
R Boyd	MEng CEng MICE (Arup)
J Burridge	MA CEng MICE MIStructE (MPA The Concrete Centre)
T Ellis	BSc MSc CEnv MIEnvSc (Arup)
M Farnetani	MArch MSc ARB BREEAM-AP (Hilson Moran)
B Gholam	CEng MIStructE (Price & Myers)
A Girao-Coelho	PhD MSc CEng (British Constructional Steelwork Association)
W Hawkins	MEng PhD (University of Bath)
T Ibell	CEng FREng PhD FIStructE FICE FHEA (University of Bath)
Q Li	PhD MArch BArch (Cundall)
A Lynes	MA MEng(Hons)(Cantab) CEng MIStructE (Webb Yates Engineers)
E Marsh	MEng GMICE (University of Cambridge)
M Moynihan	CEng MIStructE (Laing O'Rourke)
A Papakosta	MSc MEng (SCS Railways)
I Poole	MEng (Mott MacDonald)
J Prew	BSc(Hons) CEng MIStructE MICE MAPM (Hampshire County Council)
J Ratcliffe	MEng CEng FIStructE PE (scale consulting ltd)
W Rogers-Tizard	CEng MIStructE (Price & Myers)
T Ronalds	MEng CEng MIstructE (Eckersley O'Callaghan)
M Sansom	BEng PhD CEnv MICE (Steel Construction Institute)
K Symons	MEng MA MIStructE MICE CEng CPEng CMEngNZ IntPE(NZ) (New Zealand Government)
N Watson	EngD CEng MICE (Buro Happold)
F Yang	BS MEng SE(CA) (Arup)

Publishing

L Baldwin	BA(Hons) DipPub (The Institution of Structural Engineers)
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International HQ, 47–58 Bastwick Street, London EC1V 3PS, United Kingdom
T: +44(0)20 7235 4535
E: mail@istructe.org
W: www.istructe.org

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Contents

Foreword

This document supports legislation by UK Parliament to achieve net zero carbon emissions by 2050 and forms a part of the response of The Institution of Structural Engineers to implement the necessary changes in the profession to respond to the climate emergency.

Naturally, the materials that structural engineers specify must be used efficiently to create structures that are safe and durable. But it is now abundantly clear that structural engineers need to reduce the harm that manufacture and disposal of these materials cause our planet's ecosystem, which accounts for 11% of global greenhouse gas emissions. Hence, we must reduce the embodied carbon of the structures we design.

Structural engineers need an agreed set of principles for the measurement of embodied carbon to be able to make meaningful comparisons and carbon reductions across the construction industry. This will allow us to set agreed carbon target levels for structures and track the level of reduction in embodied carbon, to ensure we achieve net zero carbon by 2050.

Being able to measure and compare embodied carbon of structures is only one step in the quest for the decarbonisation of the construction industry. Yet it is an important step because it allows us to place 'embodied carbon' alongside 'embodied costs' in the design of structures — managing carbon footprint through material selection and specification, material reuse, lean design and waste reduction. An ability to quantify the benefits of low carbon design to the client and society and ensure we meet targeted reductions is crucial for the future.

This guidance will help inform structural engineers, and the professionals with whom they collaborate, about ways they can move towards net zero carbon design. The need is becoming increasingly urgent and the consequences of failure are increasingly alarming.

Dr Mike J Cook
IStructE Climate Emergency Task Group Chair

Purpose, principles and impact

Purpose

This guide provides a common set of embodied carbon calculation principles for the structural engineering community to follow. The imperative to achieve net zero carbon by 2050 must change the way we practice — and calculating carbon is a key part of this.

Calculating embodied carbon in the same rigorous way across all designs will allow meaningful comparisons to be made between structural schemes, developing our understanding of embodied carbon as well as how we can most effectively reach net zero carbon. This guidance is equally applicable to infrastructure and building projects.

The calculation of embodied carbon must become a key part of every design process. Such efforts support our immediate need to reduce resource demand and increase reuse and recycling to enable a circular economy.

This guide builds on the IStructE's portfolio of guidance documents, FAQs and articles related to embodied carbon[1], a topic that has long been on the agenda of some pioneering members of the IStructE community. It supports the sustainability related core tasks in *The Structural Plan of Work 2020*[2].

References to embodied carbon data and guidance in this document are UK-focused. Where the authors are aware of such information from other countries, it is referenced in the Appendix. This document is aligned with BS EN 15978[3], BS EN 15804[4] and RICS Professional Statement *Whole life carbon assessment for the built environment*[5].

Principles

We must:

- Achieve net zero carbon[6] before 2050
- Calculate embodied carbon[†] on all projects
- Recognise carbon as one component of sustainability
- Evaluate design decisions against their carbon impact
- Communicate carbon insights to the project team
- Advocate and engage the project team to find ways to reduce carbon impacts
- Report module-based[††] carbon data to an open source database

⇒ Suggestions, hints, common pitfalls and tips are captured in red boxes.

Key principles are contained within green boxes.

Grey boxes highlight the end of a process or calculation stage.

† As a minimum, we must calculate cradle to practical completion carbon emissions (life cycle Modules A1–A5, as explained in Section 1.1 and Figure 2.2), also known as 'upfront carbon'.
†† Stage D must always be reported separately to Stages A–C.

Impact

It is important to realise the scale of impact that our professional activities have on the climate. Buildings and construction presently account for around 40% of energy-related CO_2 emissions. Deep changes across the design, construction, use and reuse of buildings and infrastructure are required if we are to have any chance of providing a sustainable environment for the 9.7bn people, including 6.5bn city dwellers, who will share our planet in 2050.

Figure 0.1 contextualises the scale of opportunity the average structural engineer has to reduce carbon emissions in comparison to the impact the average citizen may have by making a significant environmentally-conscious change to their personal lives.

Figure 0.1: Contextualising potential impact of structural engineers†

Analysis of recently constructed buildings has demonstrated that material inefficiencies in the order of 50% are common[7]. Overdesign of buildings and infrastructure must also be tackled to reduce material demand and to help meet carbon targets.

One route to zero carbon structural design is through the reuse and life extension of existing buildings and their component parts. *Doing nothing* while meeting your client's brief requires much thought and engineering analysis but is essential if we are to dramatically cut carbon emissions. You should resist demolition wherever you can and ensure reuse in some form as a key part of every design you create. End of life discussions are thus an integral part of achieving a circular economy.

† 20% structural embodied carbon reduction achieved is based on the assumption of a structural engineer being responsible for (on average) 5,000m^2 development per year, at an average A1–A5 emissions of 200kgCO_2e/m^2 (substructure and superstructure) and achieving embodied carbon reductions of 20% (i.e. reduction of 40kgCO_2e/m^2).
*Values approximated. Return flight to New York including radiative forcing calculated using https://carbon.tips/calc. Impact of diet is an approximate value assuming a saving each week of 1–2 portions each of beef, chicken, lamb and fish, 7 × 200ml portions of dairy milk and 7 pints of beer, calculated using https://carbon.tips/diet. Driving emissions calculated assuming 10,000 miles per year in an average petrol car, using https://carbon.tips/calc.

1 Introduction to carbon calculations

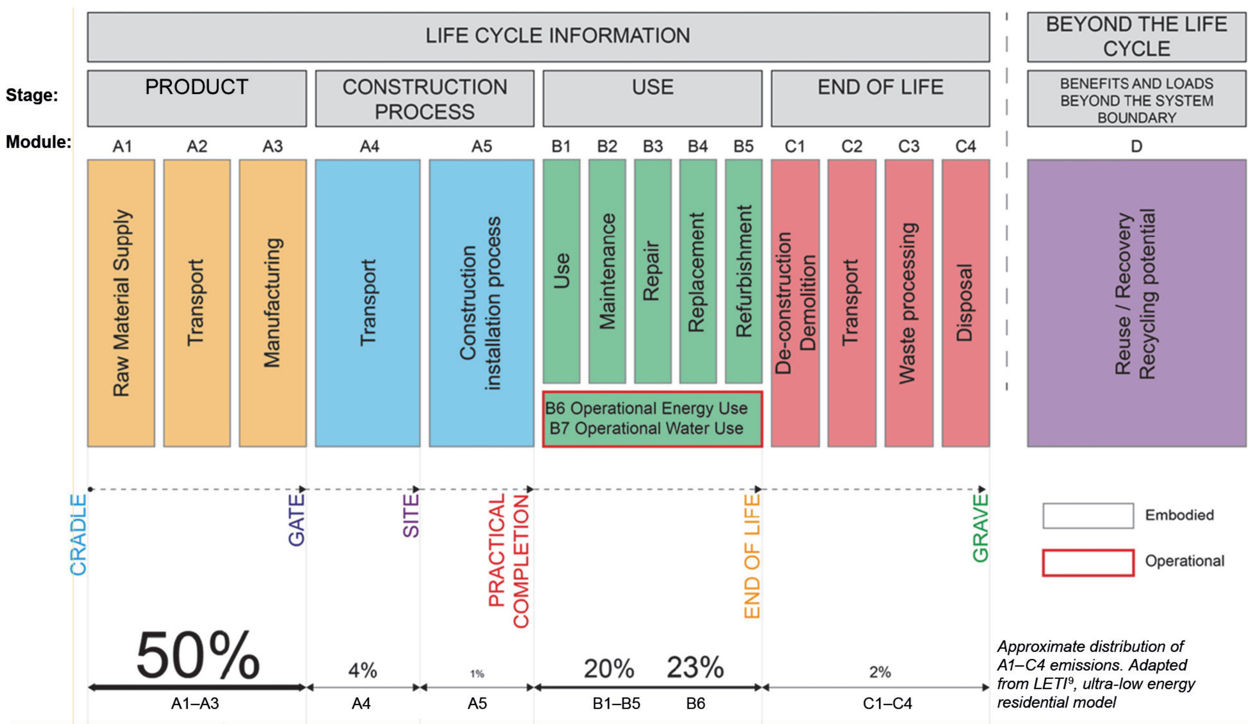
1.1 Life cycle stages and modules

To help describe the environmental impact of an asset, its life cycle is split into stages and modules as defined by BS EN 15804[4] (Figure 1.1)[†]. The environmental impact this guidance refers to is carbon dioxide equivalent emissions (kgCO_2e), also known as global warming potential (GWP).

An example split of emissions from Modules A1–C4 is shown at the base of Fig. 1.1, using example data from the LETI *Embodied Carbon Primer*[9] across all building elements for a medium scale residential building. This highlights the importance of Modules A1–A3 to Embodied Carbon Over the Life Cycle (Section 1.2).

Remember that efforts to calculate, report and reduce embodied carbon should be taken in conjunction with bigger picture discussions about the whole life performance of built assets along with emissions from land use change. Embodied carbon is just one piece of the sustainability puzzle.

Figure 1.1: BS EN 15978[3] Life cycle stages. Example split of emissions from Modules A1–C4 shown at bottom, using example data across all building elements for a medium-scale residential building. Operational carbon modules outlined in red



† Note that infrastructure projects should review PAS 2080[8], which uses a similar structure but with slightly different terminology, and the addition of a 'pre-construction stage' that consists of Module A0.

There are four life cycle stages:

- **Product stage** (also known as ‘cradle to gate’). Modules A1–A3. $kgCO_2e$ released during extraction, processing, manufacture (including prefabrication of components or elements) and transportation of materials between these processes, until the product leaves the factory gates to be taken to site. Note that recycled content of a product affects the $kgCO_2e$ released in modules A1–A3. Whether it is recycled after its end of life or not, does not affect the A1–A3 impact of the project being considered — this is taken into account in Module D
- **Construction process stage**. Modules A4 and A5. $kgCO_2e$ released during transport of materials/products to site, energy usage due to activities on site (site huts, machinery use etc.) and the $kgCO_2e$ associated with the production, transportation and end of life processing of materials wasted on site
- **Use stage**. Modules B1–B7. $kgCO_2e$ released due to use, maintenance, repair, replacement, refurbishment and operational energy and water use while the building is in use. Module B4 (replacement) is often the focus of the use stage when embodied carbon is being considered
- **End of life stage**. Modules C1–C4. $kgCO_2e$ released during decommissioning, stripping out, demolition, deconstruction, transportation of materials away from the site, waste processing and disposal of materials

There is one additional stage beyond the life cycle of the asset that is intended to provide a broader view of its environmental impacts:

- **Benefits and loads beyond the system boundary**. Module D. This estimates any net $kgCO_2e$ benefits or loads beyond the project’s life cycle associated with:
  - recycling of materials, e.g. use of scrap steel (rather than virgin iron) in steelmaking on future projects
  - energy recovered from materials, e.g. energy generated by incinerating timber products
  - full reuse of materials/products

  when compared to the standard practice/standard product it would be replacing

1.2 Terminology

This section presents terminology commonly used in industry, and thus aligns with the terminology used throughout this guide. Note that the terms are not always used consistently across all built environment publications.

Building component: A prefabricated assembly of materials that form a product with a specific function, e.g. a precast concrete floor unit, a facade unit.

Building element: A major physical part of a building that fulfils a specific function, or functions, irrespective of its design, specification or construction, e.g. floors, frame, external walls[8].

Carbon factor: Normally measured in $kgCO_2e$ per unit of product e.g. $kgCO_2e/kg$.

CEN/TC 350 Sustainability of construction works: The technical committee responsible for the development of standardised methods for the assessment of sustainability aspects of new and existing construction works, and for standards for the Environmental Product Declarations (EPDs) of construction products (Figure 1.2).

$kgCO_2e$: Carbon dioxide equivalent emissions, or ‘carbon’ for short. This can also be referred to as ‘global warming potential’ (GWP).

Environmental Product Declaration (EPD): An independently verified and registered document that communicates transparent and comparable information about the life cycle environmental impact of products.

Embodied carbon ($kgCO_2e$): Carbon emissions associated with:
- extraction and manufacturing of materials and products
- in-use maintenance and replacement
- end of life demolition, disassembly and disposal

including transportation relating to all three[9].

Embodied carbon to practical completion (kgCO_2e): Modules A1–A5. This is the carbon emissions associated with the extraction and processing of materials, the energy and water consumption used by the factory in producing products, transporting materials to site, materials wasted on site and energy used due to construction activity (also referred to as 'upfront embodied carbon')[10].

Embodied carbon over the life cycle (kgCO_2e): Carbon emissions associated with Modules A1–A5, B1–B5 and C1–C4.

Net zero carbon: When the amount of carbon emissions associated with a building's embodied and operational impacts over the life of the building, including its disposal, are zero or negative[11]. Since offsetting carbon emissions must only be a last resort, and given that there are no negative emissions options, we advise that you should view the carbon target as an absolute one: zero carbon means zero emissions.

Operational carbon (kgCO_2e): The carbon dioxide associated with the in-use operation of the building, Modules B6 and B7. This usually includes carbon emissions associated with heating, hot water, cooling, ventilation and lighting systems, as well as those associated with cooking, equipment and lifts, i.e. both regulated and unregulated energy uses[10].

Regulated energy: Energy consumed that is within the scope of building regulations.

Unregulated energy: Energy consumed that is outside the scope of building regulations.

Whole life carbon (kgCO_2e): Carbon emissions associated with Stages A–C and D, with Stage D reported separately. This may also be referred to as 'cradle to cradle'.

Figure 1.2: Relationship between selected documents developed by CEN/TC 350

Sustainability of construction works
CEN/TC 350 *https://carbon.tips/tc350*

Framework level

BS EN 15643-1 (2010)
Sustainability Assessment of Buildings – General Framework

BS EN 15643-2 (2011)
Assessment of Buildings. Framework for the assessment of environmental performance

Building level

BS EN 15978 (2011)
Assessment of environmental performance of buildings. Calculation method

PD CEN/TR 17005 (2016)
Additional environmental impact categories and indicators – Background information and possibilities – Evaluation of the possibility of adding environmental impact categories and related indicators and calculation methods for the assessment of the environmental performance of buildings

Product level

BS EN 15804 (2012) +A2 (2019)
Environmental product declarations – Core rules for the product category of construction products

PD CEN/TR 16970 (2016)
Guidance for the implementation of EN 15804

BS EN 15942 (2011)
Environmental product declarations – Communication format business-to-business

PD CEN/TR 15941 (2010)
Environmental product declarations – Methodology for selection and use of generic data

2 Calculating embodied carbon

The fundamental principle of an embodied carbon calculation is to multiply the quantity of each material by a carbon factor for the life cycle modules being considered†:

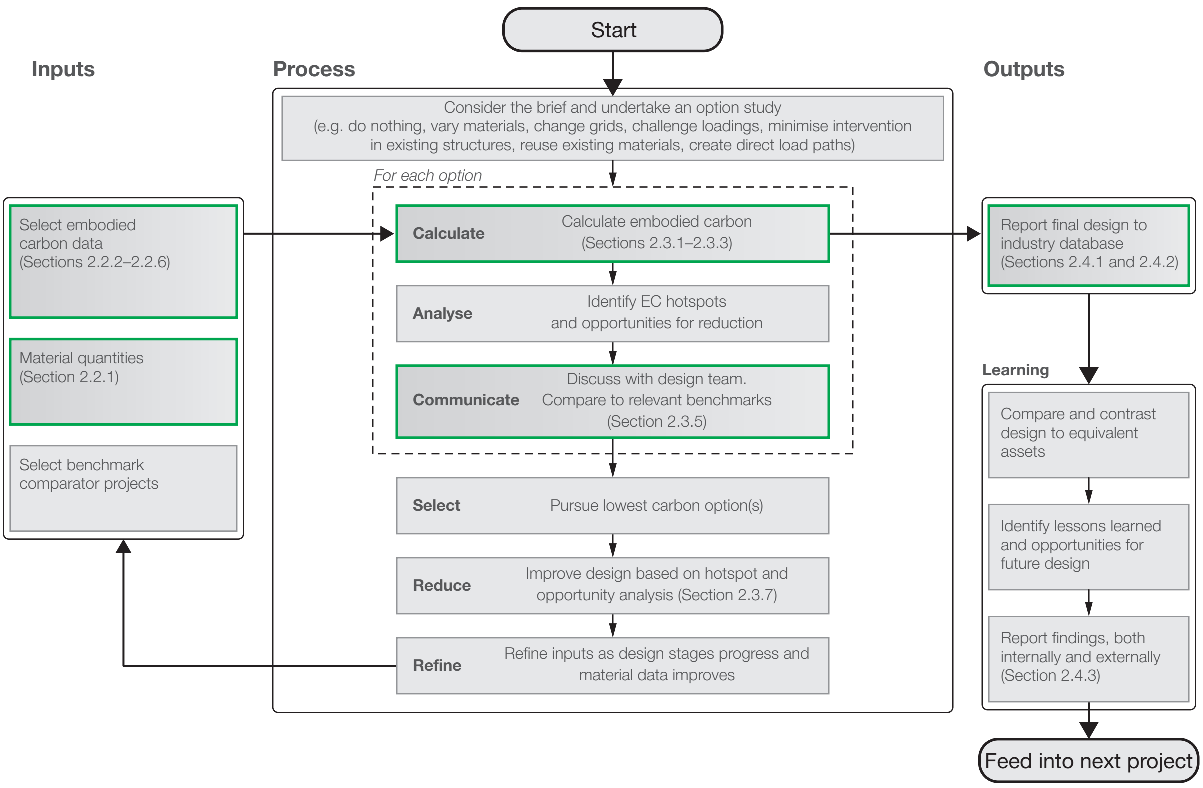
material quantity (kg) × carbon factor ($kgCO_2e/kg$) = embodied carbon ($kgCO_2e$)

Use embodied carbon as a key design metric and communicate findings to your design team members whenever there is a significant design decision to be made and at project milestones.

The most important time to calculate embodied carbon is in the early design stages. The earlier the better. It is crucial to have time and scope to make changes in light of your embodied carbon assessment.

At the end of each project, report embodied carbon data to an open source database (Section 2.4.1), and submit lessons learned to *The Structural Engineer* magazine[12]. Figure 2.1 outlines how such calculations can be integrated into any stage of a typical project. Items in green boxes are addressed in this guidance.

Figure 2.1: Calculating embodied carbon process overview (1)



† The equation shown applies to materials measured in kg, where a carbon factor in $kgCO_2e/kg$ is available. Any measure of quantity may be used, e.g. m^2, m^3, etc., as long as it corresponds to the units of the carbon factor, e.g. $kgCO_2e/m^2$, $kgCO_2e/m^3$, etc. If the unit of quantity does not correspond to the unit of the carbon factor (e.g. quantity in m^3, carbon factor in $kgCO_2e/kg$), then the quantity should be adjusted, based on the physical properties of the product, so that its units align with those of the carbon factor, or *vice versa* (e.g. by using the density, kg/m^3). For structural materials, carbon factors are commonly shown in $kgCO_2e/kg$.

2.1 Minimum scope of calculation

As a minimum for structural elements, your calculation should include Modules A1–A5 for primary substructure and superstructure elements. Also include Module B4 for facades if within your scope of design.

2.1.1 Minimum scope: life cycle stages and modules

This guide stipulates that the minimum life cycle scope of embodied carbon assessments for structural elements is to include life cycle Modules A1–A5 (embodied carbon to practical completion). There are several reasons for this:

- A1–A5 emissions will be released before 2050. They are therefore the emissions we most urgently need to understand and minimise to keep global warming within 1.5°C
- We have most certainty over A1–A5 emissions data
- Typically, the majority of the embodied carbon of structures is associated with Modules A1–A5, therefore this should be the focus of our carbon reduction efforts

However, best practice is to consider whole life embodied carbon (Stages A–C plus D), so that we not only minimise embodied carbon emissions today but also consider the future emissions impacts of using the asset, durability, longevity, end of life scenarios, reusability and recyclability. This will ensure that future emissions and resource consumption are also kept to a minimum. If Stages A–C are calculated, it is important to report A1–A5 results alongside A–C results.

Be aware that design for minimum upfront carbon can run counter to discussions on future flexibility. Where design teams are advocating longer spans, or higher floor loading, use your carbon calculations to quantify the environmental impact of such choices. You will need to weigh up the certainty of an increase in carbon emissions *today* with the probability of a future change in use, based on the local context. Changes in use may be achieved by means other than building-in extra upfront capacity; for example, by being flexible about what an office space or residential space really needs, or by appropriately designed strengthening works applied in the future. The same discussions should occur when demountable or reusable component design is discussed. A key challenge today is the reuse and life extension of existing buildings.

Note that the RICS Professional Statement *Whole life carbon assessment for the built environment*[5] states that the minimum scope of assessment for a whole building carbon assessment is Modules A1–A5 + B4 (for facades) + B6. This guidance aligns with that document, as Modules B4 and B6 rarely need to be considered in a structural design.

2.1.2 Minimum scope: building elements

This guide stipulates that the minimum building element scope of embodied carbon assessments for structural elements is to include primary substructure and superstructure. You should also calculate the embodied carbon associated with all other elements within your scope of works.

For buildings, the Building Cost Information Service's (BCIS) *Elemental Standard Form of Cost Analysis* (SFCA)[13] summarised in Table 3 of RICS' *Whole life carbon assessment for the built environment*, are used to categorise elements included in a carbon assessment. For a structural engineer, the building element categories most likely to be included in an embodied carbon calculation are given in Table 2.1 of this guidance, with the minimum scope highlighted in green.

⇒ Table 2.1 (right hand column) suggests a way to categorise structural elements included in your calculation to allow better insights into where the embodied carbon lies, and thus how to minimise it. If you do categorise elements in a different way to the BCIS SFCA categories, show how they relate in your design reports, for transparency with other disciplines.

Table 2.1: BCIS SFCA building element categorisations relating to structural elements, mapped against a possible way of breaking down structural elements for carbon analysis. Minimum scope of calculation highlighted in green

Building part/element group (BCIS SFCA)		Building element (BCIS SFCA)	Possible breakdown of structural elements for carbon analysis
0	Facilitating works	0.2 Major demolition works	
		0.3 Temporary support to adjacent structures	
		0.4 Specialist ground works	
1	Substructure	1.1 Substructure	Foundations (including pile caps)
			Ground bearing slab
			Basement retaining walls
2	Superstructure	2.1 Frame	Columns
			Braces
		2.2 Upper floors	Beams
			Slabs (incl. permanent formwork)
		2.3 Roof	Roof beams
			Roof slab
		2.4 Stairs and ramps	Stairs and ramps
		2.5 External walls	Structural external walls
		2.7 Internal walls and partitions	Structural internal walls
6	Prefabricated buildings and building units	6.1 Prefabricated buildings and building units	
7	Work to existing building	7.1 Minor demolition and alteration works	

Note: Complete category list can be found in Table 3 of RICS' *Whole life carbon assessment for the built environment*.

For the embodied carbon of structural schemes to be meaningfully compared, you should also consider whether any other building elements are dictated by the structural system. Liaise with the wider design team to understand what these may be. A common example is fire protection to structural elements. A1–A3 embodied carbon factors (ECFs) for common fire protection materials are given in Table 2.3 so that they can be included in your assessment if necessary.

Considering whole life and whole building carbon emissions requires collaboration across the project team, which this guide strongly advocates. Although structural engineers need to be fluent in the embodied carbon of structures to contribute to achieving a zero-emissions built environment, we must not lose sight of how our designs affect emissions associated with the work of other disciplines.

⇒ Coordinate assessments across teams to ensure you know who is responsible for which building elements. Your scope of calculation should at least reflect what you are responsible for designing and this should be clearly reported.

2.2 Inputs

The inputs described in Table 2.2 need to be obtained to calculate embodied carbon for the respective life cycle modules.

Table 2.2: Inputs required for embodied carbon assessments

	Input required	Life cycle module	Section reference
Inputs required for A1–A5 (to practical completion)	Material or product quantities	All stages	Section 2.2.1
	A1–A3 carbon factors	A1–A3	Section 2.2.2.1
	Distance, mode emissions intensity of transportation of materials to site	A4	Section 2.2.3
	On site material wastage rates	A5	Section 2.2.4.1
	Site activities emissions	A5	Section 2.2.4
Additional inputs for A–C (over the life cycle)	Building element replacement cycle	B4	Section 2.2.5.1.1
	Asset lifespan (reference study period)	B4	Section 2.2.5.1.1
	Demolition and deconstruction emissions	C1	Section 2.2.5.2.1
	Distance and mode emissions intensity of transportation of materials away from site	C2	Section 2.2.5.2.2
	End of life scenarios	C3 and C4	Section 2.2.5.2.3
Additional inputs for A–D (whole life carbon)	End of life scenarios	D	Section 2.2.6
	Difference between A1–A3 carbon factors of the secondary product and the substituted product	D	Section 2.2.6

Sections 2.2.1–2.2.6 describe how to obtain these inputs (with references to relevant sources of information), and how to create a carbon factor for each of the life cycle modules within the scope of your embodied carbon assessment. Note that this guidance focuses on UK references. However, the same principles apply to embodied carbon calculations globally.

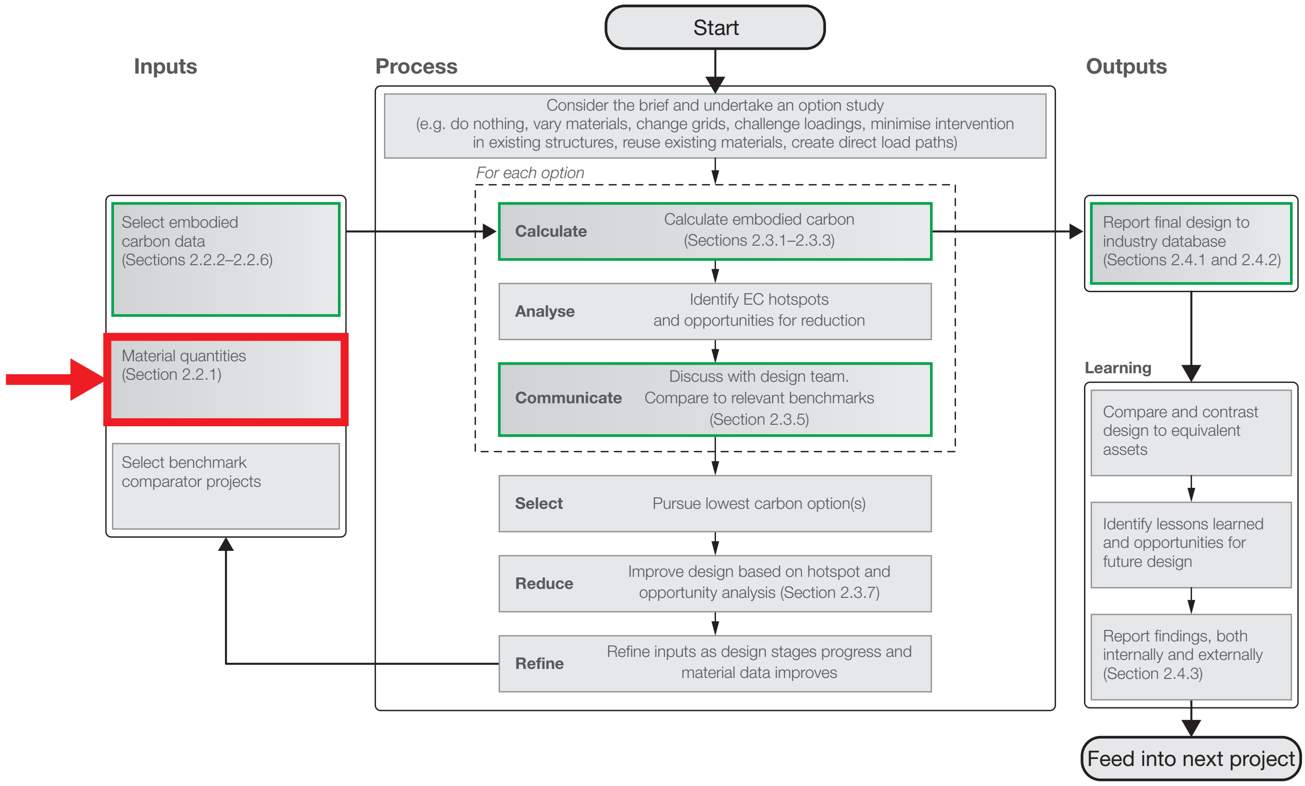
For Stage B, we focus on B4 (replacement) as:

- Module B1 (use) is generally insignificant for structural materials
- Very little data exists for Modules B2 (maintenance) and B3 (repair)
- Module B5 (refurbishment) refers to planned changes in use defined at the start of the project
- Modules B6 and B7 address operational carbon and are outside the scope of this guide

Section 2.2.5.1 contains more detail on Stage B modules.

2.2.1 Material quantities

Figure 2.2: Calculating embodied carbon process overview (2)



DO NOT be deterred from calculating embodied carbon at early design stages because of uncertainty in material quantities.

Material quantities† can be calculated in a number of different ways, depending on the stage of design and the tools available, including:

- Manual calculations
- BIM models
- Structural analysis models
- Scheming manuals (e.g. *Structural Engineer's Pocket Book: Eurocodes*[14])
- Preliminary calculations on representative/repeated structural elements
- Previous project experience
- A quantity surveyor's cost plan††

Uncertainty in material quantities will decrease over the course of a project. Update your calculations regularly to reflect this.

† The carbon data you use may dictate how you report your quantities, whether it is in kg, m^3 or m^2. Use material properties to toggle between these different measures as needed.

†† Obtaining quantities from the quantity surveyor's (QS) cost plan is the least favourable option in terms of being able to feed embodied carbon information into the design process, as there is a time lag between designing and receiving this information to calculate embodied carbon.

⇒ Be aware of common elements that are often only partially modelled but need to be included in the carbon count: paint and intumescent coverings, piles and footings, concrete blinding, connections (for steel frames a % allowance is usually made), bolts, studs, permanent decking or formwork, rebar laps, etc. Check the specification against your material lists.

⇒ Use quantities collected during construction to create an as-built carbon assessment.

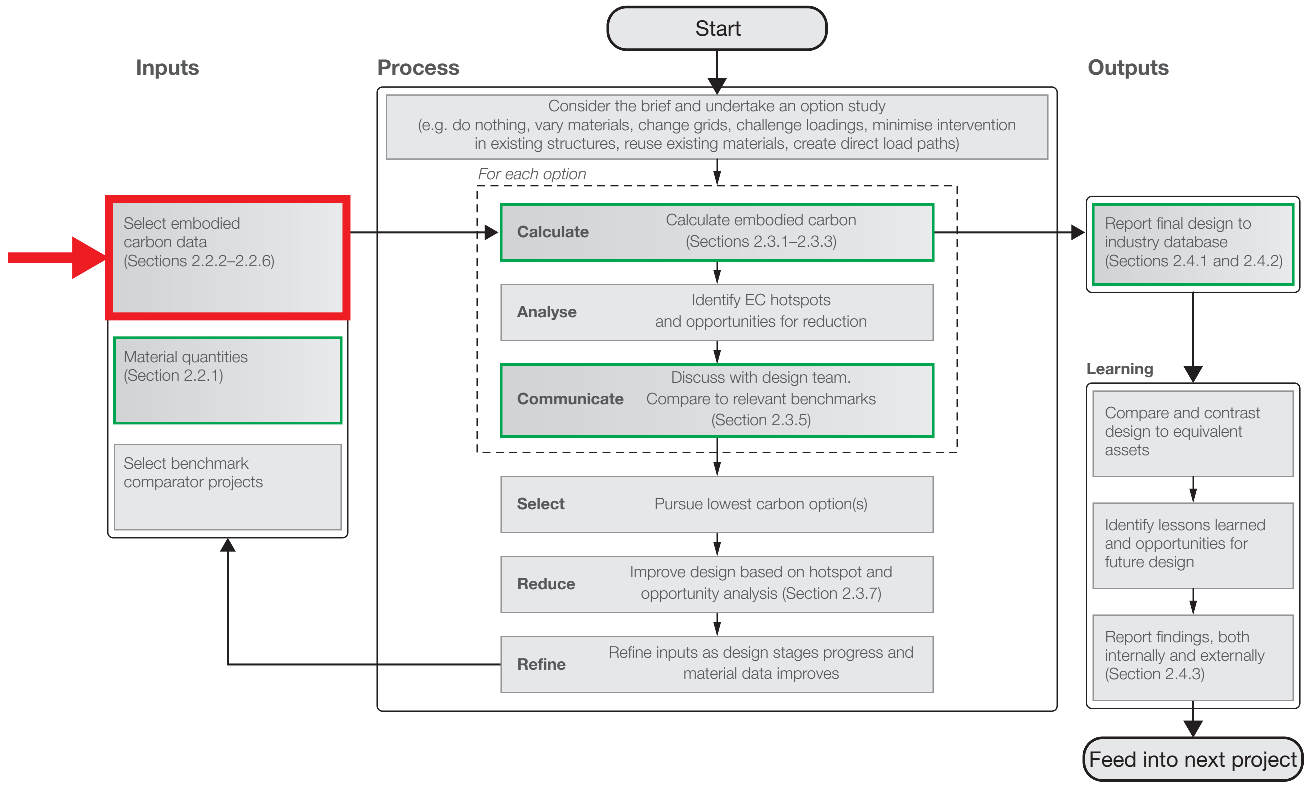
Now you have a list of materials and their quantities (usually in kg or m^3).

2.2.2 Inputs for A1–A5 calculation

2.2.2.1 Stage A1–A3 carbon factors

Modules A1, A2 and A3 are very likely to constitute the majority of structural embodied carbon over the life cycle of a project.

Figure 2.3: Calculating embodied carbon process overview (3)



The A1–A3 carbon factor† depends on:

- Location where project will be constructed (when using average values typically provided by region or country)
- Location where the products/components are to be manufactured (when supply chain is better understood and component origin is known)
- The material specification

The range in embodied carbon can be large. For example, the A1–A3 carbon factor for UK-produced reinforcement bar could be as low as 0.684kgCO_2e/kg, while a UAE-produced bar with no recycled content could be closer to 2.13kgCO_2e/kg. To get the most accurate carbon assessment and therefore make the best decisions, at the start of a project, ask your client or a local contractor how they normally source their materials. If you are unable to determine this, use the default values in Table 2.3.

There are a number of different sources of material carbon factors. Some express industry averages for a supplier, a group of suppliers or for a country. Others express the embodied carbon of a specific product.

⇒ Choose a factor that best reflects your understanding at the time of calculation, for the source and specification of the material. In the early design stages, this usually means selecting regional or industry average carbon factor data, such as those outlined in Table 2.3. Flag your uncertainty, be transparent about any assumptions made and revisit your choice of A1–A3 carbon factors at later design stages.

DO NOT be deterred from calculating embodied carbon at early design stages because of uncertainty of carbon factors.

The *Inventory of Carbon and Energy*[15], commonly known as 'ICE', is an open source material carbon factor database. It contains UK-specific data as well as European and global averages, based on EPDs, some of which is referenced in Table 2.3. Similar databases from other countries are listed in the Appendix.

2.2.2.1.1 Unknown material or product specifications

Use default material specifications unless you wish to commit to driving a particular material specification through the design process, and/or until you know more about where/how materials will be sourced.

Default values for commonly used structural materials (based on open source data available at the time of publication) can be obtained from Table 2.3. Note that material ECFs are likely to change over time as production processes are made more efficient and the electricity grid decarbonises. If you cannot find materials that will be used on your project in Table 2.3, the ICE database or Section 2.2.2.1.2 of this guidance contains a list of EPD sources to look through.

⇒ The energy supply mix in different geographical areas can impact the carbon emissions associated with production of a product. Until product specific EPDs have been chosen it is sensible to use national, regional or international average data points.

⇒ Table 2.3 is not exhaustive and is intended only to be used as your starting point. You should look for EPDs that best suit your projects and use those in your calculations. Note also that the table does not cover reclaimed materials, where A1–A3 carbon factors may be close to zero, highlighting again the need for reuse to be a key part of your design.

† Modules A1–A3 are normally aggregated and reported as a single carbon factor. In some circumstances, the modules may be reported individually; check each Environmental Product Declaration (EPD) that you use, to confirm this.

Table 2.3: Suggested embodied carbon factors (ECFs) of common construction materials

Material	Type	Specification/details	A1–A3 ECF ($kgCO_2e/kg$)	Data source
Concrete	*In situ*: piling, substructure, superstructure	Unreinforced, C30/37, UK average ready-mixed concrete EPD[a] (35% cement replacement)	0.103	Ref. 16
		Unreinforced, C32/40, 25% GGBS cement replacement[b]	0.120	Ref. 15
		Unreinforced, C32/40, 50% GGBS cement replacement	0.089	Ref. 15
		Unreinforced, C32/40, 75% GGBS cement replacement	0.063	Ref. 15
		Unreinforced, C40/50, 25% GGBS cement replacement	0.138	Ref. 15
		Unreinforced, C40/50, 50% GGBS cement replacement	0.102	Ref. 15
		Unreinforced, C40/50, 75% GGBS cement replacement	0.072	Ref. 15
	Generic non-structural *in situ* concrete	Unreinforced, C16/20, 0% cement replacement with CEM I	0.113	Ref. 15
	Mortar/screed	1:4 cement:sand mix[c] with CEM I cement	0.163	Ref. 15
		1:4 cement:sand mix with average UK cement mix[d]	0.149	Ref. 15
	Precast concrete	Unreinforced, C40/50 with average UK cement mix	0.178	Ref. 15
		Reinforced, 150mm prestressed hollow core slab: British Precast Flooring Federation average EPD	50.2 $kgCO_2e/m^2$	Ref. 17

Table 2.3: *Continued*

Material	Type	Specification/details	A1–A3 ECF ($kgCO_2e/kg$)	Data source
Steel	Reinforcement bars	UK: UK CARES Sector Average EPD	0.76	Ref. 18
		Worldwide: Worldsteel LCI study data, world average	1.99	Ref. 15
	PT strands	Assume the same as reinforcement bars		
	Structural sections	UK open sections: British Steel EPD	2.45	Ref. 19
		UK hollow sections: TATA EPD	2.50	Ref. 20
		Europe (excl. UK): Bauforumstahl[e] average EPD	1.13	Ref. 21
		Worldwide: Worldsteel LCI study data, world average	1.55	Ref. 15
	Plate	UK: Assume the same as 'structural sections — UK open sections'		
		Europe (excl. UK): Bauforumstahl average EPD	1.13	Ref. 21
		Worldwide: Worldsteel LCI study data	2.46	Ref. 15
	Galvanised profiled sheet (e.g. for decking)	UK: TATA Comflor® EPD	2.74	Ref. 22
		Europe: PPA Europe EPD	2.36	Ref. 23
		Worldwide: Worldsteel LCI study data, hot dip galvanised steel, world average	2.76	Ref. 15
Blockwork	Precast concrete blocks	Lightweight (AAC) blocks	0.280	Ref. 15
		Dense blocks	0.093	Ref. 15
Brick	Single engineering clay brick	UK: BDA generic brick	0.213	Ref. 15
	Brick wall	Single skin wall with mortar 1:4 CEM I cement:sand mix	$38.0 kgCO_2e/m^2$	Ref. 15
		Double skin wall with mortar 1:4 CEM I cement:sand mix	$81.9 kgCO_2e/m^2$	Ref. 15

Table 2.3: *Continued*

Material	Type	Specification/details	A1–A3 ECF ($kgCO_2e/kg$)	Data source
Stone	Granite	Granite	0.70	Ref. 15
	Limestone	Limestone	0.09	Ref. 15
	Sandstone	Sandstone	0.06	Ref. 15
Timber, excl. carbon sequestration[f,g]	Manufactured structural timber	CLT, 100% FSC/PEFC	0.437	Ref. 15
		Glulam, 100% FSC/PEFC	0.512	Ref. 15
	Studwork/framing/ flooring	Softwood, 100% FSC/PEFC	0.263	Ref. 15
	Formwork	Plywood, 100% FSC/PEFC	0.681	Ref. 15
Aluminium	Sheet	European consumption (31% recycled content)	6.58	Ref. 15
		Worldwide consumption (31% recycled content)	13.0	Ref. 15
	Extruded profiles	European consumption (31% recycled content)	6.83	Ref. 15
		Worldwide consumption (31% recycled content)	13.2	Ref. 15
Glass	General	Generic	1.44	Ref. 15
	Toughened	Generic	1.67	Ref. 15
Plasterboard	Partitioning/ceilings	Minimum 60% recycled content	0.39	Ref. 15
Intumescent paint	For steelwork	Amotherm Steel WB EPD	2.31	Ref. 24

Notes:
[a] Covers 93% of production from member companies of the British Ready-Mixed Concrete Association.
[b] The ICE database has a wide range of concrete mixes, including PFA (pulverised fuel ash) cements. Section 2.2.2.1.3 for more information.
[c] The ICE database has many more cement:sand ratios to choose from.
[d] Taken from average UK sector cement EPD: 86.1% clinker, 0.04% GGBS, 3.4% fly ash, 4.8% gypsum, 5.1% limestone, 0.56% MACs, by weight.
[e] Bauforumstahl is a group of European steel producers including ArcelorMittal, Peiner Träger and Stahlwerk Thüringen.
[f] The ICE database also includes timber A1–A3 embodied carbon factors including sequestration.
[g] See Section 2.2.2.1.5.
Data is current at time of publication. Check sources to ensure accuracy at time of your calculation.

Note that for the steel A1–A3 ECFs in Table 2.3, values are presented based on production location. As steel is a continentally and globally traded product, a better ECF estimate would be based on average consumption in the country/region your project is based. However, at the time of publication, the authors believe that such information has not yet been published. In the absence of consumption-based data for each country/region, it is recommended that a steel A1–A3 ECF is selected so that the production location matches the project location. For example, for a project in the UK using steel open sections, use 2.45kgCO_2e/kg[19].

2.2.2.1.2 Known material or product specifications

The accuracy of your carbon assessment will be greatly improved through the use of product-specific carbon data. As your design progresses, so too should your carbon assessment certainty.

EPDs provide detailed environmental impact information for a material or product, including A1–A3 carbon factors. Use these when you can be more certain about which countries or manufacturers your materials/products will be sourced from. You can also use information from EPDs to help influence which products should be used to fulfil a desired performance specification. Ask manufacturers for their EPDs or search for them online.

> ⇒ Make sure you always ask the manufacturer for the EPDs of their products — creating demand for good environmental practices is a positive action.

Otherwise, you can obtain EPDs from these websites:

- Environdec: https://www.environdec.com
- Institut Bauen und Umwelt: https://ibu-epd.com/en/published-epds/
- EPD Ireland: https://www.igbc.ie/epd-search/
- BRE Green Book Live: http://www.greenbooklive.com/
- Carbon Leadership Forum: http://www.carbonleadershipforum.org/resources/
- ECO Platform: https://www.eco-platform.org/list-of-all-eco-epd.html
- Transparency Catalog: https://www.transparencycatalog.com/
- Climate Earth: https://www.climateearth.com/greenmixselector/

See the Appendix for a list of carbon factor databases from various parts of the world.

EPDs often include only Modules A1–A3, so take care if you are combining EPD data with other sources that may include additional modules (e.g. A–C), as you will need to fill in the gaps (or at least note the limitations of such quick calculations). If you wish to use A4 and A5 data from an EPD, always check the assumptions within these calculations align with the project-specific circumstances and/or the advice contained within Section 2.3 of this guidance.

BS EN 15804[4] now requires construction products and materials EPDs to declare Modules A1–A3, C1–C4 and D. This will increase the availability of data for Modules C and D and can be integrated into your whole life carbon calculations, provided all materials and products are able to be considered in the same manner.

EPDs are normally valid for five years, and their validity date will be displayed on the EPD. Make sure the data you are using is valid.

For more information, refer to the ASBP briefing papers on EPDs[25–27].

2.2.2.1.3 Concrete

The embodied carbon of concrete is most heavily influenced by the amount of Portland Cement (PC) contained within it.

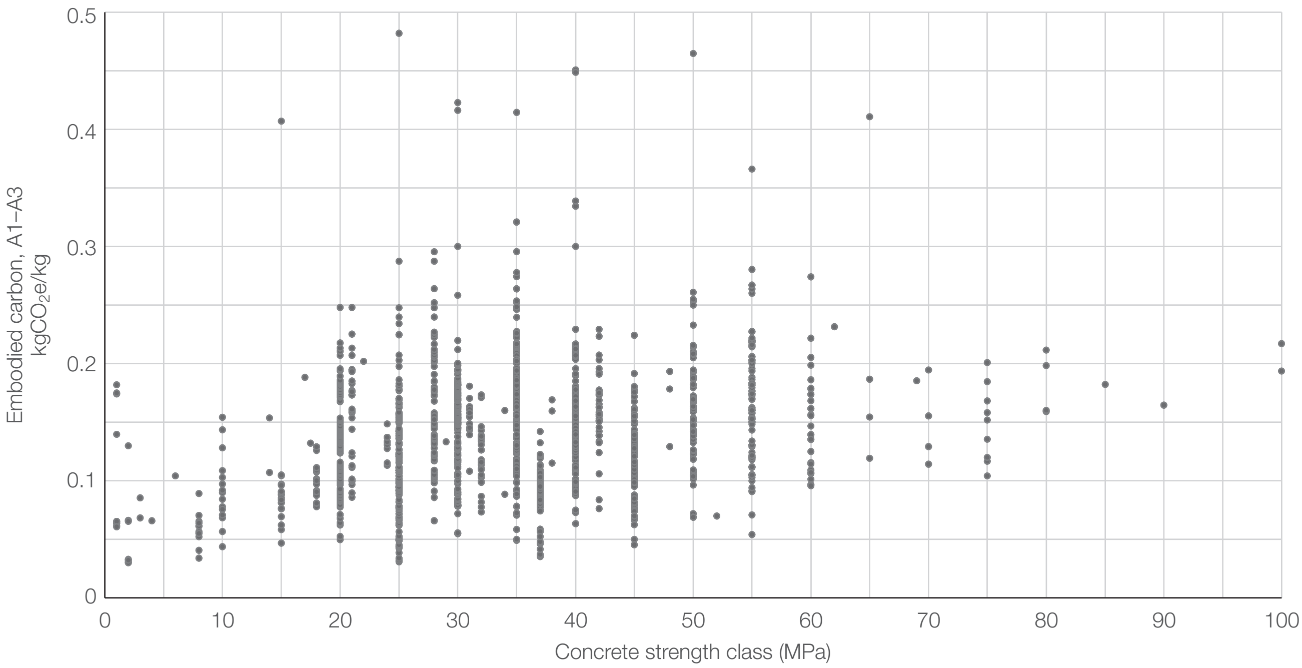
To reduce the embodied carbon of concrete, PC can be partially (or completely[†]) substituted by other cementitious materials commonly known as 'cement replacements', the most common of which are Ground Granulated Blast Furnace Slag (GGBS)[††], Pulverised Fuel Ash (PFA)[†††] and limestone. It should be noted that the production of GGBS and PFA are tied to carbon intensive industries. There are limited amounts produced globally, and efforts to decarbonise energy supplies and steel production should result in decreased supplies in the future. Lehne and Preston[28] and Allwood *et al*.[29] provide further insights into possible low carbon concrete technologies that may be available in the future.

[†] Products such as Cemfree and LoCem use 100% GGBS alongside an alkali-activated cementitious material (AACM).
[††] Waste product from blast oxygen furnace (BOF) route of production of steel.
[†††] Waste product from coal-fired power plants.

Using a lower concrete strength grade will also reduce the total cementitious content requirement and thus embodied carbon. However, this may or may not reduce the embodied carbon of a reinforced concrete section, depending on the embodied carbon associated with any resulting increased demand for steel reinforcement and/or concrete volume to meet performance requirements.

Purnell and Black[30] have shown that for a given compressive strength, embodied carbon values of concrete can vary by a factor of around three through varying the amount of PC. A similar trend is seen in Figure 2.4, where EPD data from more than 1500 specific concrete mixes is plotted. For more insights on the variation of concrete and concrete constituent ECF, refer to Anderson and Moncaster[31]. Note that it may be possible to achieve your desired concrete strength with considerably less carbon than you imagined.

Figure 2.4: Example of possible variation in embodied carbon for concrete mixes. The concrete strength class reported is highest end in given ranges for those mixes



Cement type affects early age strength gain; generally, the higher the proportion of PC replacements the slower the strength gain. It is worth noting that for this reason, currently precast concretes typically have lower limits on the proportion of PC replacements (typically up to 25%), and so have higher embodied carbon, as concrete strength gain affects the production rate of precast products. You should request low embodied carbon mixes for precast products whenever you can[32].

The amount of PC specified in a concrete mix is a function of application-specific requirements for strength, durability, workability and curing speed. Your concrete mix design should be optimised to achieve the functional requirements with minimum embodied carbon by carefully considering the mix of constituent materials. A concrete mix is typically designed by a concrete producer from a concrete specification. It is recommended that you engage the concrete producer when seeking low carbon concretes.

Refer to the MPA's *Specifying Sustainable Concrete*[33] for guidance. Note that material quantity reduction should always be your primary objective, followed by appropriate specification.

The ICE database provides the embodied carbon of a variety of concrete mixes of different strengths and degrees of PC replacement, some of which are included in Table 2.3. If you cannot find a carbon factor for a concrete that matches your concrete mix specification, you can calculate the embodied carbon of a specific mix using the freely available *Concrete Embodied Carbon Footprint Calculator*[34]. Alternatively, for a more accurate estimate, ask your concrete supplier for a mix-specific embodied carbon calculation.

2.2.2.1.4 Steel

The A1–A3 carbon factor of steel varies depending on its recycled content and its production method: basic oxygen furnace (BOF) or electric arc furnace (EAF). BOF is a fossil fuel-fired (mostly coal) production process that produces steel from high proportions of virgin iron ore compared to scrap metal (maximum 30% scrap[35], and typically 13% in the UK). EAF is a process powered by the electricity grid and can produce steel made with a very high recycled content (up to 100%[35], and typically 97% in the UK). Steel produced by EAF and with high recycled content generally has a much lower A1–A3 carbon factor than BOF-produced steel, and this may reduce further in future as electricity grids decarbonise.

Steel A1–A3 carbon factors also vary by steel product (e.g. hollow section, open section, plate) as the amount of processing they go through correlates to the amount of energy used in the manufacturing process, and some products are better suited to a specific production technique e.g. EAF or BOF. For example, hollow sections typically have a slightly higher carbon factor than open sections (I-sections), and thin products such as steel plate are typically produced by BOF.

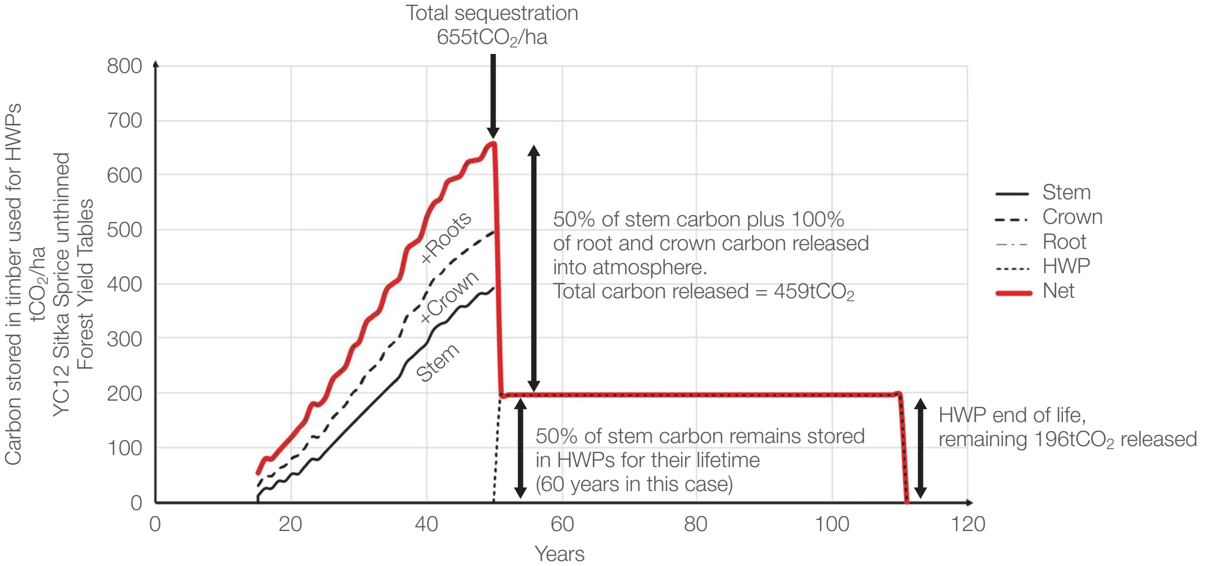
At early design stages, when the production method and source of steel is not known, a market average embodied carbon factor for steel in the geographical region of the project (i.e. average carbon factor of steel consumed in that region) is recommended. However, in the absence of regional market average data, it is recommended that a steel A1–A3 ECF is selected so that the production location corresponds to the project location. Table 2.3 presents steel A1–A3 ECFs based on production location, as regional market average steel carbon factors are not known to the authors at the time of publication.

Table 2.3 quotes A1–A3 embodied carbon factors (ECFs) from the ICE database for worldwide averages, and from EPDs for European and UK average ECFs. These A1–A3 ECFs are based on the 100:0 recycling method, which effectively only takes the benefits from recycled scrap content in its production into account. Any benefits from recycling steel at end of life should be accounted for in Module D (Section 2.2.6), if included in your assessment, not in Modules A1–A3. The ICE database provides more information on different methods of accounting for recycled content and recycling rate.

2.2.2.1.5 Timber

Carbon dioxide is removed from the atmosphere as trees grow — via photosynthesis, known as 'sequestration'. The carbon element of this CO_2 is temporarily stored within timber until it is released at end of life in the form of a greenhouse gas (CO_2 or CH_4), for example by burning or decomposition of the timber. An example of this is illustrated in Figure 2.5.

Figure 2.5: Example of carbon stored in timber used for Harvested Wood Products (HWPs) over time[a,b,c]



Notes:

a Data obtained from Morison *et al*[36].

b Does not consider other greenhouse gases such as methane CH_4 or nitrous oxide N_2O. Further information can be found in Morison *et al*[36].

c Does not include CO_2 emissions due to manufacture or transport.

Here we propose that carbon sequestration — part of Module A1 for timber products — should always be considered in an embodied carbon calculation, **provided that the timber originates from a sustainably managed forest with FSC or PEFC (or equivalent) certification**. However, in line with RICS guidance[5], whether the sequestration value is added to the total reported embodied carbon value depends on the scope of calculation:

- Modules A1–A5: do not include sequestration within the A1–A5 total value but report it separately alongside the A1–A5 total (Figure 2.8)
- Modules A–C: include sequestration within the total A–C value reported (Fig. 2.8)

Emissions in Stage C account for the sequestered carbon released back into the atmosphere at the end of life of the product. **Unless** reuse of the component can be guaranteed, these end of life (Modules C3 and C4) emissions will either balance or exceed (depending on end of life scenario) the carbon sequestration in Module A1. It is therefore extremely important to implement design measures to maximise the lifespan of timber elements to ensure the sequestered carbon is locked up for as long as possible before being released.

The rationale behind not including carbon sequestration within the total A1–A5 value, but reporting it separately alongside is:

- Including sequestration in the A1–A5 total would typically result in a negative value for A1–A5 embodied carbon (i.e. showing a net extraction of carbon emissions from the atmosphere). This could allow engineers to show that less efficient use of timber results in lower, i.e. a greater negative value of, embodied carbon. This must be avoided to prevent unnecessary use of resources
- We should not ignore the fact that carbon sequestration happens, therefore we should show it

In the absence of product specific data, **carbon sequestered**[†] **can be assumed as -1.64kgCOe per kg of timber**[††].

This value is derived from Equation (2.1), which is adapted from BS EN 16449[37]:

$$S_{CO_2} = \frac{44}{12} \times cf \times \frac{1}{1 + \frac{\omega}{100}} \tag{2.1}$$

Where

S_{CO_2} = carbon sequestered, per kilogram of product, from the atmosphere (kgCO_2/kg)
cf = carbon fraction of woody biomass (oven dry mass) (assume 0.50 in the absence of product specific information)
ω = moisture content (assume 12% in the absence of product specific information)

It should be noted that EPDs for timber products are now required to include the benefits of sequestration in the A1–A3 carbon factor, under the 2019 update to BS EN 15804[4,†††]. When reporting A1–A5 calculations, the sequestered carbon calculated using Eqn. (2.1) should be extracted from the A1–A3 carbon factor in the EPD when reporting A1–A5 calculations, yielding the carbon emissions due to production processes alone. In some cases, EPDs do extract sequestration from the A1–A3 total, which would remove the need to use Eqn. (2.1). Note that the energy used to dry timber products to a suitable moisture content can be significant.

The ICE database provides two sets of A1–A3 carbon factors for timber products, one including sequestration and the other excluding sequestration (the latter is included in Table 2.3). End of life emissions associated with timber products (e.g. CO_2 release from incineration or CO_2 and CH_4 release during landfill) are reported in Stage C (Section 2.2.5.2).

Morison *et al*.[36] and Ramage *et al*.[39] provide useful starting points for readers who wish to delve further into carbon balances in forests and the use of timber in construction.

† Carbon sequestered in a timber product is also known as 'biogenic carbon'.
†† This assumes default values given in the RICS guidance[5] of carbon factor woody biomass = 50% and moisture content = 12%.
††† BS EN 15804:2019 follows the guidance of BS EN 16485:2014[38].

2.2.2.1.6 Temporary works

Where temporary works for the construction phase requires the manufacture of new products, these production impacts should be accounted for in Modules A1–A3. Examples might include bespoke steelwork for propping works, or the fabrication of bespoke concrete moulds. Emissions from their transport to site (Module A4), their use on site and any waste of them occurring on site (Module A5) should also be accounted for in their respective life cycle modules.

Where temporary works make use of materials that already exist and have been used on other construction sites, e.g. scaffolding poles, A1–A3 emissions can be assumed to be zero but A4 and A5 emissions must be accounted for. It is strongly recommended to use materials that already exist for temporary works, e.g. by using elements that can be rented.

Now you have a list of materials, their quantities and a corresponding list of ECFs for Modules A1–A3.

2.2.3 Module A4 carbon factors

Module A4 is likely to account for a modest percentage of structural embodied carbon over the life cycle of a building project. For heavy civil works, Module A4 emissions may be more significant.

Module A4 is concerned with transport of materials or products from the factory gate to the construction site, and the transport of construction equipment (cranes, scaffolding, etc.) to and from the site.

⇒ Remember that some journeys comprise multiple legs over different transport modes. You need to include the whole journey in your calculations.

⇒ Reuse of components, materials or products that are locally sourced and transported over short distances will help to reduce both Module A4 and overall project emissions.

The carbon factors for transportation of each material are calculated by multiplying the transportation distances by the respective transportation modes' emissions factors (Equation (2.2)):

$$ECF_{A4,i} = \sum_{mode} (TD_{mode} \times TEF_{mode}) \tag{2.2}$$

Where

$ECF_{A4,i}$ = transport to site for *i*th material
TD_{mode} = transport distance for each transport mode considered
TEF_{mode} = transport emission factor for each transport mode considered

True transportation embodied carbon factors ($ECF_{A4,i}$) for each material will not be known until the project is completed and the material transportation modes and distances have been recorded. In the absence of precise information, the information that follows can be used to estimate $ECF_{A4,i}$.

Transport emissions factors (TEF) can be estimated using UK data for transport emissions (Table 2.4). Note that these are for the UK only, and rail transport emissions (for example) depend on the electric/diesel mix in each country.

⇒ The units of TEF ($gCO_2e/kg/km$) are from $kgCO_2e$ per tonne.km data points[40]. This metric is rather crude and may be best suited to early design stages. The dataset[40] also provides $kgCO_2$ per vehicle km data, which provides a more refined calculation if you know the transport requirements for specific materials and products.

Table 2.4: Transport emissions factors

Mode	TEF_{mode} ($gCO_2e/kg/km$)	Source
Road transport emissions, average laden	0.10650	Ref. 40[a]
Road transport emissions, fully laden	0.07524	Ref. 40[b]
Sea transport emissions	0.01614	Ref. 40[c]
Freight flight emissions	0.59943	Ref. 40[d]
Rail transport emission	0.02556	Ref. 40[e]

Notes:
[a] For HGV (all diesel), all HGVs, average laden.
[b] For HGV (all diesel), all HGVs, fully laden.
[c] For cargo ship, container ship, average.
[d] International, to/from non-UK, without radiative forcing.
[e] Freight train.

Transport distances should be estimated based on project-specific scenarios.

In the absence of such data, transport distances for projects in the UK can be estimated using the default distances contained in the RICS guidance[5] and those given in Table 2.5 along with the resulting ECF_{A4} value.

Table 2.5: Default ECF values for Module A4 for the UK ($TD_{mode} \times TEF_{mode}$)

A4 transport scenario	km by road	km by sea	$ECF_{A4,i}$ ($kgCO_2e/kg$)
Locally manufactured	50	–	0.005 $50km \times 0.10650gCO_2e/kg/km / 1000$
Nationally manufactured	300	–	0.032
European manufactured	1500	–	0.160
Globally manufactured	200	10000	0.183

The values in Tables 2.4 and 2.5 should be used with care and updated with improved data as your project progresses. Take care to ensure that transport distance comparisons are fair and reasonable for each product and material.

⇒ Ask your manufacturers for predicted logistics for the supply chain to get a better idea of Module A4 emissions.

2.2.4 Module A5 carbon factors

Module A5 is likely to account for a small, but not insignificant, percentage of structural embodied carbon over the life cycle of a building project†.

In this guide, Module A5 emissions are broken down into two subsets. Emissions associated with the volume of each material that is wasted on site are identified as **A5w** emissions (Equation (2.3)). Emissions due to general construction activities e.g. from energy use of machinery and temporary site offices, are identified separately as **A5a** emissions (Eqn. (2.5)).

2.2.4.1 Material wastage on site (A5w)

$$ECF_{A5w,i} = WF_i \times (ECF_{A13,i} + ECF_{A4,i} + ECF_{C2,i} + ECF_{C34,i}) \quad (2.3)$$

Where

$ECF_{A5w,i}$ = construction waste embodied carbon factor for *i*th material
WF_i = waste factor for *i*th material given by Equation (2.4)
$ECF_{C2,i}$ = transportation away from site, calculated in the same way as $ECF_{A4,i}$ but transport distance is assumed to be 50km by road if taken for reuse or recycling elsewhere (default assumption from RICS guidance[4]), i.e. 0.005kgCO_2e/kg, or average distance between two closest landfill sites for landfill or incineration
$ECF_{C34,i}$ = waste processing and disposal emissions associated with construction waste material (Section 2.2.5.2.3)
$ECF_{A13,i}$ Includes carbon sequestration for any timber products wasted during construction, as Module A5 also accounts for the end of life of timber products wasted in $ECF_{C34,i}$. As explained in Section 2.2.2.1.5, sequestration should be included where end of life emissions are accounted for

$$WF_i = \left(\frac{1}{1-WR_i} - 1\right) \quad (2.4)$$

Where

WR_i = waste rate (proportion of a component that ends up as waste during installation and/or construction process) of *i*th material, which can be estimated using WRAP Net Waste Tool data[41] (Table 2.6 of this guidance)

During design, it will be necessary to estimate the waste rate based on industry average data. The most recently published industry data, from the WRAP Net Waste Tool, is summarised for structural materials and systems in Table 2.6. These data are a guide only, and you are encouraged to find updated information on waste rates from contractors you work with or in specific EPDs for products you are using.

⇒ It is important to make it a requirement of the contractor to collect the waste rate data for the different products used on site. This information can then be used to produce an accurate as-built Module A5 embodied carbon calculation and inform industry average data on waste rates.

⇒ During construction, waste rates should be minimised where possible, and efforts must be made to find reuse or recycling streams for any unused materials and components. This is key to enabling the construction industry to transition to a circular economy.

Note that if components are prefabricated off site, the material waste rate on site is likely to be lower than if it is constructed on site. This is reflected in the UK construction site waste rate data presented in Table 2.6. For pre-fabricated products, wastage in the factory should be taken into account in Module A3.

† For heavy civil works, A5 may be more significant.

Table 2.6: A selection of waste rate data from the WRAP Net Waste Tool: Guide to reference data[41,a]

Material/product	WR (waste rate)	WRAP Net Waste Tool reference	WF (waste factor)
Concrete *in situ*	5%	Table 2, Concrete *in situ*	0.053
Mortar	5%	Table 2, Gypsum products	0.053
Screed	5%	Table 2, Screed	0.053
Concrete precast (beams and frames)	1%	Table 2, Concrete precast (Large precast elements)	0.010
Steel reinforcement	5%	Appendix 1, Frame: *In situ* concrete frame generic Table 2, Ferrous metals	0.053
Steel frame (beams, columns, braces)	1%	Appendix 1, Frame: Steel frame generic	0.010
Concrete blocks	20%	Table 2, Bricks and blocks	0.250
Brick	20%	Table 2, Bricks and blocks	0.250
Stone	10%	Table 2, Stone	0.111
Timber frames (beams, columns, braces)	1%	Appendix 1, Frame: timber frame	0.010
Timber floors (joists, board)	10%	Appendix 1, Floor: wooden floor	0.111
Timber formwork	10%	Table 2, Processed timber	0.111
Aluminium frames	1%	Appendix 1, Conservatories: aluminium frame	0.010
Glass	5%	Table 2, Glass	0.053
Plasterboard (for boarding)	22.5%	Table 2, Plasterboard Table 3, Boarding	0.290
Sprayed cementitious fire protection to steel	10%	Table 3, Cementitious sprays	0.111

Notes:
[a] The WRAP Net Waste Tool presents baseline and good practice waste rates for each material/system. Only the baseline waste rates are presented here.

2.2.4.2 Temporary works materials

Common examples of temporary works are:

- Timber formwork for *in situ* RC frames
- Steel frames used to stabilise existing structures during construction

Where materials or products used for temporary works have been newly manufactured for the project, these emissions are accounted for in Modules A1–A3 (Section 2.2.2.1.6).

Where the project is reusing temporary works products (e.g. steel propping, guard rails, scaffolding) you should estimate how much of the material is wasted (i.e. cannot be used on the next project) and account for these emissions in A5w using Eqn. (2.3).

Temporary works that are being reused from a previous project and will be reused on a future project should only include transport related emissions of moving the temporary works to and from site (captured in A4) and around the site (captured in A5a).

When calculating the quantities of temporary works materials, consider how many times they may be used on the project, e.g. timber formwork may be used up to 5 or 6 times on one project. Speak to the temporary works contractor to get a better estimate quantity of temporary works material required. Alternatively, the designer may make assumptions based on experience or research.

It should be noted that, for new builds, unless significant temporary works are required, their contribution to the total structural embodied carbon is likely to be relatively small.

2.2.4.3 Excavation

The carbon impacts of excavation on site should be accounted for in Module A5. The removal of excavated material from the site is accounted for in A5w (Section 2.2.4.1), and the emissions from on-site machinery used to excavate the material are accounted for in A5a (Section 2.4.4.4).

In most cases, $ECF_{A5w,i}$ is equal to $ECF_{C2,i}$ — the emissions released in transporting the excavated material away from site (Section 2.2.5.2.2). In some cases, waste processing may be required for excavated material, in which case $ECF_{C34,i}$ should be taken into account, but there are no production or transportation to site emissions. In other words, in Eqn. (2.3) for excavation material, $WF_i = 1$, $ECF_{A13,i} = 0$, $ECF_{A4,i} = 0$, and often $ECF_{C34,i} = 0$.

Until we have better data on site activities emissions, we can assume that on-site excavation machinery emissions are accounted for in Eqn. (2.5). See Section 2.2.4.4.

2.2.4.4 Site activities (A5a)

Site activity emissions can be estimated from on-site electricity consumption and fuel use, and should be monitored during construction to contribute to an accurate as-built embodied carbon calculation at practical completion (Section 2.4.2). Any site activity emissions data collected can also be used to inform estimates of A5a emissions in future projects.

In the absence of project-specific data, prior to construction starting, A5a emissions can be estimated based on industry studies or previous project data. In the UK, the RICS guidance[5] provides a rate of 1400kgCO_2e per £100,000 construction cost for the whole building to be used in the absence of site-specific data.

For superstructure and substructure only, a factor of this figure can be assumed based on a predicted proportion of site activity emissions (based on construction effort, required machinery and time) due to construction of these elements. As a preliminary estimate, this may be in the order of 50% resulting in a rate of 700kgCO_2e per £100,000 for A5a emissions of substructure and superstructure only.

In the absence of more accurate data, using the metric in the RICS guidance[5], **A5a** emissions are calculated based on the construction cost (Equation (2.5)):

$$EC_{A5a} = CAEF \times \frac{PC}{100{,}000} \qquad (2.5)$$

Where

EC_{A5a} = embodied carbon from construction site activities
PC = project cost
$CAEF$ = construction activities emission factor of 700kgCO_2e/£100,000 for superstructure and substructure only, or 1400kgCO_2e/£100,000 for whole building

⇒ Ask your contractor to record on-site emissions and feed this data into the as-built carbon assessment. Note that there are available credits for doing this in environmental certification schemes, e.g. BREEAM.

⇒ Encourage your contractor to minimise diesel fuel use and supply electricity from renewable sources to minimise A5a emissions.

Now you have a list of materials, their quantities and a corresponding list of ECFs for Modules A1–A5.

2.2.5 Additional inputs for A–C calculations

The information in this section primarily follows recommendations provided in the RICS guidance[5].

2.2.5.1 Stage B carbon factors

Modules B1–B5 together are likely to account for a very small, and sometimes negligible, percentage of structural embodied carbon over the life cycle.

Module B4 (replacement) is typically the focus of the Use Stage (Stage B) in embodied carbon assessments.

Guidance on Modules B1–B3 and B5 are included here for information. You should be aware that:

- Module B1 (use) is generally insignificant for structural materials
- Very little data exists for Modules B2 (maintenance) and B3 (repair)
- Module B5 (refurbishment) refers to planned changes in use defined at the start of the project
- Modules B6 and B7 address operational carbon and are outside the scope of this guide

Stage B carbon factors depend on the lifespan of the built asset, which in carbon assessments is represented by the reference study period (RSP). The default RSP to be used for building projects is 60 years, and 120 years for infrastructure projects[5].

2.2.5.1.1 B4 Replacement

Module B4 relates to the embodied carbon associated with replacing building elements during the life cycle of the asset (the RSP) e.g. replacement of the facade during the lifetime of the building. It is part of the minimum scope of embodied carbon calculation where facades are assessed.The inputs required are:

- Estimated component lifespan for *i*th material, CL_i.
  For structural and substructure elements, the default should be equal to the asset reference study period, i.e. they are not replaced during the building life cycle.
  For paints (e.g. intumescent) and other building elements, e.g. facades and MEP services, the lifespan is likely to be shorter than the RSP. To obtain the component lifespan, the designer can ask the product manufacturer or use industry experience or evidence. Ideally, the designer will advocate that a commitment is made to maximise component lifespans through a robust maintenance regime.
  In the absence of manufacturer information or occupier commitments, default values from the RICS guidance[5] should be used for component lifespans.
- Asset RSP.
  The RSP to be used is 60 years for buildings, and 120 years for infrastructure[5].

The carbon factor for Module B4 is a product of the number of times a component is replaced in the built asset's life cycle and the sum of the A and C carbon factors (Equation (2.6)):

$$ECF_{B4,i} = \left\lceil \frac{RSP}{CL_i} - 1 \right\rceil \times (ECF_{A13,i} + ECF_{A4,i} + ECF_{A5w,i} + ECF_{C2,i} + ECF_{C34,i}) \qquad (2.6)$$

Where

$ECF_{B4,i}$ = replacement emissions for *i*th material
CL_i = estimated component lifespan for *i*th material
RSP = asset reference study period
$\left\lceil \frac{RSP}{CL_i} - 1 \right\rceil$ means round up the value of $(RSP/CL_i) - 1$ to the next integer
$ECF_{A13,i}$ includes carbon sequstration for any timber products replaced during the RSP because Module B4 also accounts for the end of life of timber products replaced in $ECF_{C34,i}$. As explained in Section 2.2.2.1.5, sequestration should be included where end of life emissions are accounted for

It should be noted that at the time of calculation, both the asset reference study period and component lifespans are assumptions, as it is difficult to accurately predict future actions. These assumptions should be clearly stated and justified when reporting embodied carbon.

2.2.5.1.2 Further information on B modules
B1 Use
Regarding structure, Module B1 (use) emissions are generally insignificant for structural materials.

Concrete surfaces exposed to the atmosphere absorb CO_2 during a built asset's life cycle through the carbonation process. This is estimated to account for up to 2.5% reabsorption of the CO_2e emitted in the Product Stage (Modules A1–A3)[41].

Most concrete manufacturers include an allowance for this in their EPDs. If using manufacturers' EPDs to quantify carbonation, check the assumptions contained within the EPD to ensure they match the conditions of your project, e.g. check the study period and atmospheric exposure assumed.

B2 and B3 maintenance and repair
Very little data is available to inform carbon factors for maintenance (B2) and repair (B3) for structural materials and it is assumed that emissions from B2 and B3 activities are negligible for structure.

B5 Refurbishment
Module B5, different to B4 (replacement), is defined as planned alteration or improvement works to enable the asset to cater for a desired future function identified and quantified at the outset[5]. This generally corresponds to a change of use and significant works to several parts of the building.

2.2.5.2 Stage C carbon factors

Modules C1–C4 are likely to account for a small percentage of structural embodied carbon over the life cycle, unless timber products are used.

Note that the certainty of carbon factor data for the end of life (EoL) of a built asset is very low, as it relates to activities in the distant future. However, project EoL scenarios should be developed to inform whether design measures can be implemented to ensure the lowest emissions scenario is enabled at the EoL. This section provides carbon factor estimates to use to calculate Stage C emissions based on existing industry guidance (primarily the RICS guidance[5]). If other assumptions are made in your calculations, they should be clearly stated.

2.2.5.2.1 C1 Demolition and deconstruction
In the absence of information from a contractor, an average rate from the RICS guidance[5] can be assumed (Equation (2.7)):

$$EC_{C1} = 3.4\text{kgCO}_2\text{e/m}^2\text{ GIA} \quad (2.7)$$

2.2.5.2.2 C2 Transportation
Transportation of materials away from site at EoL is calculated in exactly the same way as A4 transportation emissions, but the waste processing or disposal facilities are likely to be local to the site, so the transportation distances are likely to be shorter. Default assumptions from the RICS guidance[5] can be used (Table 2.7).

Table 2.7: Default values for Module C2 ($TD_{mode} \times TEF_{mode}$)

EoL scenario	km by road	$ECF_{C2,i}$ ($kgCO_2e/kg$)
Reuse/recycling on site	0	0.00
Reuse/recycling elsewhere	50	0.005 50×0.10650 $gCO_2e/kg/km/1000$
Landfill/incineration	Average between 2 closest landfill sites	0.005 (based on 50km by road)

2.2.5.2.3 C3 and C4 Waste processing and disposal
Carbon factors for waste processing for reuse, recovery or recycling (C3) and disposal (C4) are often grouped together in embodied carbon assessments as the two scenarios are mutually exclusive.

⇒ Suitable project-specific scenarios for Modules C3 and C4 should be developed based on the project team's intentions to minimise embodied carbon or justified based on precedent and current EoL practices[5].

Data for C3 and C4 emission factors, $ECF_{C34,i}$ should be taken from EPDs if available, and if the products specification is known. As mentioned in Section 2.2.2.1.2, it should be noted that EPDs are now required to report Modules C3 and C4 ECFs. Where EPD data for Modules C3 and C4 is unavailable, the default carbon factor in Equation (2.8) can be used:

$$ECF_{C34,i} = 0.013kgCO_2e/kg \text{ waste} \quad (2.8)$$

Timber EoL emissions
If your project uses timber, Modules C3 and C4 emissions are likely to be significant, unless it can be guaranteed that the timber elements are reused. Timber C3 and C4 emissions can vary and are dependent on the EoL scenario; reuse, recycling, incineration or landfill. EPDs for timber products present the emissions calculated for C3 and C4 as well as the associated assumed EoL scenario combination.

Table 2.8 shows the variation that can be seen in ECF_{C34} for timber products based on the assumed EoL scenario. Until further guidance is released, UK-based projects may use the Wood for Good EPD EoL scenario combination (right hand column of Table 2.8)[42]. However, further guidance, data collection and data transparency are required on this to provide more robust timber product ECF_{C34} values for use in different geographical regions.

Note that, as described in Section 2.2.2.1.5, if EoL (Modules C3 and C4) emissions associated with timber products are included in the embodied carbon assessment, so too should carbon sequestration in Modules A1–A3, **provided that the timber originates from a sustainably managed forest with FSC or PEFC (or equivalent) certification**.

Concrete EoL carbonation
Similar to Module B1 (use), concrete can absorb CO_2 through the carbonation process at the EoL.

After demolition of the asset and before the resulting crushed concrete (hardcore) is used elsewhere, carbonation rates can increase as the concrete surface area to volume ratio is increased. The Concrete Centre estimates that during this time up to a further 5% of the concrete A1–A3 emissions can be reabsorbed, based on the assumption that, on average, concrete crushed on site at EoL sits on site for 26 weeks before being removed[43]. In some locations the time that crushed concrete may spend on site is much shorter, resulting in a much smaller percentage of A1–A3 emissions reabsorbed.

Table 2.8: Timber EoL scenarios and associated approx. C3 and C4 carbon factors

EoL scenario	Description	UK default C3 and C4 emissions factors	RICS timber EoL scenario[5]	Wood for Good EPD, UK Kiln Dried Sawn Softwood[42], EoL scenario
Reuse	For use in new built assets	0	–	–
Recycling	For use in animal bedding/surfaces, panel board products	1.67kgCO_2e/kg[43]	–	55%
Incineration for energy recovery	Sequestered carbon is re-released as CO_2	1.64kgCO_2e/kg (equal to default sequestered carbon — Section 2.2.2.1.5)[5]	75%	44%
Landfill (no gas recovery)[a]	Sequestered carbon is re-released as CO_2 and CH_4	2.15kgCO_2e/kg[5]	25%	1%
		Total ECF_{C34}	1.77kgCO_2e/kg	1.64kgCO_2e/kg

Note:
[a] Modern landfill sites often employ techniques to capture gases from decomposition of organic matter.

2.2.6 Additional inputs for A–D calculations

Module D represents the estimated benefits or burdens of materials and components beyond the EoL of the built asset under consideration. It provides a good metric of circularity[†], an attribute that is key to enabling the decarbonisation of the construction industry.

Calculating Module D emissions requires quantifying the difference in emissions between utilising recovered materials (through reuse, recycling or incineration) and producing a functionally equivalent product with standard practices and market averages. Equation (2.9) represents this difference in emissions for reuse and recycling:

$$ECF_{D,i} = ECF_{A13,\text{secondary product}} - ECF_{A13,\text{substituted product}} \quad (2.9)$$

These impacts are beneficial when the future use of the material after EoL results in practices that are less carbon intensive than the business as usual use case, e.g. steelmaking from 100% scrap steel (secondary product) has lower A1–A3 carbon emissions than steelmaking from 80% virgin iron and 20% scrap steel (substituted product). Therefore, Module D impacts are dictated by the EoL scenarios for each material or component; either reuse, recycling (e.g. of steel), incineration (e.g. of timber products) or landfill.

[†] Circularity is a term commonly used to describe the ability of something to contribute a low carbon circular economy[44,45]. Describing the circular economy is not within the scope of this document.

EoL scenarios are uncertain for most materials (as they relate to actions taken at some point in the distant future), therefore Module D impacts can also be uncertain. For materials that retain value at the end of life, eg. those materials that can easily be recycled or reused, the likely range of end of life scenarios may have some certainty, but the carbon impacts associated with each scenario may still vary significantly.

⇒ Engineers should consider the most plausible combination of EoL scenarios when calculating Module D, and clearly state the basis of their assumptions.

⇒ Make sure that the EoL scenarios for timber products assumed for Module D match those assumed for Modules C3 and C4 for each respective scenario assessed.

Where available, Module D impacts can be taken from EPDs for specific materials or products, and the associated assumptions of EoL scenarios should be checked against project-specific information and scenarios. Table 2.9 shows ECFs for Module D taken from the EPDs in Table 2.3 (where provided).

Table 2.9: Module D carbon factors with corresponding EoL scenarios, largely taken from EPDs presented in Table 2.3

Material	Type	Specification/details	D ECF ($kgCO_2e/kg$)	EoL scenario assumption	Data source
Steel	Reinforcement bars	UK: UK CARES EPD	0.351	92% recycling	Ref. 18
		Worldwide: Worldsteel LCI study data, world average	-0.79	85% recycling	Ref. 15
	PT strands	Assume the same as reinforcement bars			
	Structural sections	UK open sections: British Steel EPD	-1.60	92% recycling 7% reuse	Ref. 21
		UK hollow sections: TATA EPD	-1.53	92% recycling 7% reuse	Ref. 22
		Europe (excl. UK): Bauforumstahl average EPD	-0.413	88% recycling 11% reuse 1% landfill	Ref. 23
		Worldwide: Worldsteel LCI study data, world average	-0.34	85% recycling	Ref. 15
	Plate	UK: Assume the same as 'structural sections — UK open sections'			
		Europe (excl. UK): Bauforumstahl average EPD (group of producers)	-0.413	88% recycling 11% reuse 1% landfill	Ref. 23
		Worldwide: Worldsteel LCI study data	-1.16	85% recycling	Ref. 15
	Galvanised profiled sheet (e.g. for decking)	UK: TATA Comflor® EPD	-1.15	85% recycling	Ref. 24
		Europe: PPA Europe EPD	-1.38	90% recycling 10% landfill	Ref. 25
		Worldwide: Worldsteel LCI study data, hot dip galvanised steel, world average	-1.32	85% recycling	Ref. 15
Timber[a]	Studwork/framing/ flooring	Kiln dried sawn softwood (UK)	-0.524	55% recycling 44% incineration 1% landfill	Ref. 42[b]

Notes:
[a] Note that for timber, the end of life scenarios used for Module D must match those used for Modules C3–C4.
[b] This EPD was not provided in Table 2.3, but has been included here as it contains information on Module D that the ICE database does not. The EPD does not provide the carbon factor for the different EoL scenarios separately.

⇒ Where the relevant data is unavailable, and for further guidance on Module D, refer to the RICS guidance[5] and consider Module D qualitatively.

Module D impacts should always at least be considered qualitatively. Even if the scope of the assessment is Modules A1–A5, you should consider whether your design would be reusable or recyclable beyond the EoL of the project.

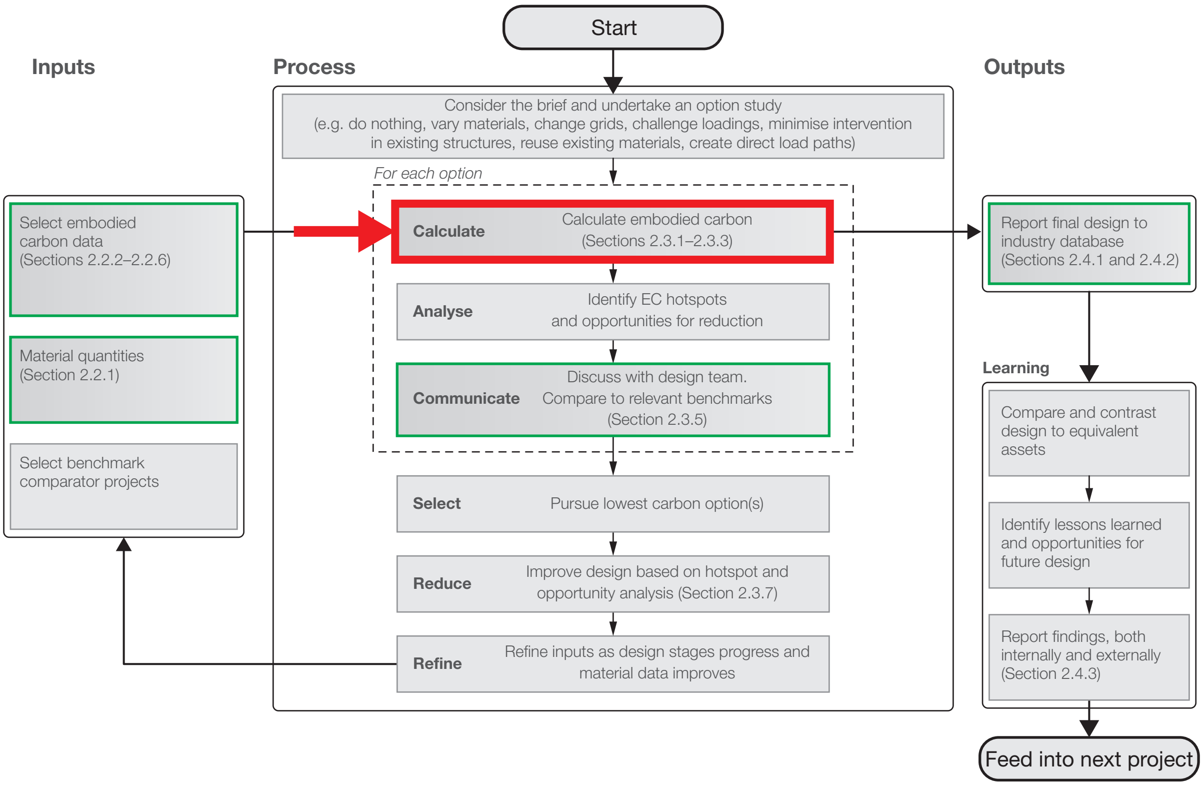
The most important and beneficial EoL scenario is the reuse of existing assets, components or materials. Offering the potential for reuse in future, e.g. through providing appropriate flexibility or designing to enable deconstruction at EoL, will reduce future A1–A3 emissions and maximise the Module D benefits of your project. Additionally, reusing existing resources on your project will minimise A1–A3 emissions. Reuse of components requires design flexibility as you make use of an inventory of available parts that constrain and inform your design choices[46–48].

Designing to maximise recycling potential in future requires consideration of the impact of coatings, treatments, combining different materials into composites and the ease of dismantling components on recyclability.

2.3 Process

2.3.1 Calculation

Figure 2.6: Calculating embodied carbon process overview (4)



The fundamental principle of an embodied carbon calculation is to multiply the quantity of each material by its carbon factor.

The majority of embodied carbon for a building is typically associated with lifecycle modules A1–A3 (cradle to factory gate), which also represent immediate emissions for which data is most readily available for.

Calculating embodied carbon of different design options at early design stages is critical for reducing the embodied carbon of a project, while retrospective calculation of embodied carbon at the end of the design stages and at the end of construction is important for contributing your project data to industry benchmarking databases.

You should make embodied carbon calculations:

- Whenever there is a significant decision to be made, e.g. comparing structural framing and floor options in early design stages
- At the end of every stage of design
- At the end of the design process
- At the end of construction

Undertaking calculations at the end of construction is a vital step in improving future calculations. By collecting real information, you can improve the accuracy and reduce uncertainty around your future embodied carbon calculations during the design stages.

2.3.1.1 Modules A1–A3

A1–A3 emissions are the easiest to calculate as the carbon factors are most readily available. They are also those that structural engineers have most immediate control over, and generally form most of the structural embodied carbon.

A1–A3 emissions are calculated by multiplying the quantities of each material by the A1–A3 carbon factor for each of those materials. The basic calculation is given in Equation (2.10):

$$EC_{A13} = \sum_{i=1}^{n} [Q_i(ECF_{A13,i})] \qquad (2.10)$$

Where

EC_{A13} = total embodied carbon for life cycle Modules A1–A3 ($kgCO_2e$)
Q_i = quantity of material (kg)
$ECF_{A13,i}$ = Module A1–A3 embodied carbon factor for ith material ($kgCO_2e/kg$)

Using Eqn (2.10) you have calculated A1–A3 embodied carbon for all materials in your design.

⇒ Think about how to arrange your calculations, and whether you want to calculate embodied carbon by building element (each broken down into its constituent materials), or by material (with total quantities obtained from multiple building elements).

⇒ If you are using EPD specific data, make sure you check the functional or declared unit (for example, kg or m^3), and match this to your calculation to ensure the units of EC_{A13} are output in $kgCO_2e$.

2.3.1.2 Modules A1–A5

A1–A5 emissions are calculated in the same way as A1–A3 emissions, but additional carbon factors for material transport to site and material wastage on site (specific to each material) are included, plus an allowance for emissions associated with general construction activities.

Calculating the A1–A5 emissions (cradle to practical completion) is the minimum scope for a structural embodied carbon calculation (substructure and superstructure).

The A1–A5 calculation is given by Equation (2.11):

$$EC_{A15} = EC_{A13} + \sum_{i=1}^{n} [Q_i(ECF_{A4,i} + ECF_{A5w,i})] + EC_{A5a} \qquad (2.11)$$

Where

EC_{A15} = total embodied carbon for life cycle Modules A1–A5 ($kgCO_2e$)
$ECF_{A4,i}$ = transportation to site (Module A4) ECF for ith material, Eqn. (2.2)
$ECF_{A5w,i}$ = on-site construction waste (Module A5) embodied carbon factor for ith material, Eqn. (2.3)
EC_{A5a} = construction activities emissions (Module A5), Eqn. (2.5).

As explained in Section 2.2.2.1.5, carbon sequestration associated with timber products should not be reported within the A1–A5 value, but reported separately alongside the A1–A5 total.

Using Eqn (2.11) you have calculated A1–A5 embodied carbon ($kgCO_2e$) for your design. Total biogenic carbon sequestered must also be calculated and reported separately.

2.3.1.3 Modules A–C

A calculation that captures the carbon emissions over the asset's whole life cycle (cradle to grave) includes Module B (Use) and Module C (End of Life) in addition to A1–A5.

In this guide we have focused on calculating product and construction stage embodied carbon (Modules A1–A5), as your immediate priority should be to minimise these emissions to address the climate emergency. Modules B and C relate to uncertain data points, and generally represent a small, but not insignificant, proportion of structural (superstructure and substructure) life cycle embodied carbon (unless timber products are used, Section 2.2.5.2) and the associated emissions may only occur in the distant future.

However, you should not dismiss life cycle stages B, C and D, but instead acknowledge that consideration of the whole life cycle (Stages A–C plus D) is best practice for sustainable design. At a minimum:

⇒ Coordinate with the design team to understand any interdependencies between structural design solutions and Stage B emissions associated with other design disciplines e.g. facades and MEP.

⇒ Be aware that Stage C and/or Stage D considerations can contribute to lower A1–A5 emissions of future projects.

In principle, the calculation for A–C is the same as for modules A1–A5: find a carbon factor that represents the impact of each material at modules B1–B5 and C1–C4 and multiply it by the respective material quantities.

The A–C calculation (including only Module B4 from Stage B for the reasons described in Section 2.2.5.1) is given by Equation (2.12):

$$EC_{AC} = EC_{A15} + \sum_{i=1}^{n} [Q_i(ECF_{B4,i} + ECF_{C2,i} + ECF_{C34,i})] + EC_{C1} \quad (2.12)$$

Where

EC_{AC} = total embodied carbon for life cycle Stages A–C ($kgCO_2e$)
EC_{A15} = total embodied carbon for Modules A1–A5
$ECF_{B4,i}$ = replacement (Module B4) embodied carbon factor for the ith material Eqn (2.6)
$ECF_{C2,i}$ = transportation away from site at EoL (Module C2) embodied carbon factor for ith material (Section 2.2.5.2.2)
$ECF_{C34,i}$ = waste processing and disposal (Modules C3 and C4) embodied carbon factor for ith material (Section 2.2.5.2.3)
EC_{C1} = demolition and deconstruction (Module C1) activities emissions (Section 2.2.5.2.1)

Using Eqn (2.12) you have calculated Stage A–C embodied carbon ($kgCO_2e$) for your design.

2.3.1.4 Module D

Benefits and burdens from reuse, recovery and recycling of materials after the life of the building (Module D) must always be reported separately to all other life cycle stages.

Assessing Module D can contribute to quantifying holistic environmental impact and provide a measure of circularity of a project.

It can be calculated in the same way as A1–A3 emissions; multiply the material quantity by an emissions factor, Equation (2.13):

$$EC_D = \sum_{i=1}^{n} [Q_i(ECF_{D,i})] \quad (2.13)$$

Where

EC_D = total embodied carbon for Module D
$ECF_{D,i}$ = embodied carbon factor for Module D of *i*th material

You should work with your design team to develop project-specific scenarios for the possible future use of components beyond EoL. A single project may have multiple scenarios, and each should be realistic and feasible. Explore each scenario thoroughly and report it clearly within the carbon section of your design stage report.

2.3.2 Normalising results

Carbon values should be normalised:

- **For all projects:** by the functional unit of the asset that describes the performance characteristics of the system[8], e.g. net internal area (NIA) for offices and residential, or km for bridges, roads, railway lines, power lines and pipelines. More examples can be found in the RICS guidance[5]
- **Additionally, for buildings:** by the gross internal area (GIA)[49]. For buildings projects, embodied carbon is most commonly quoted as a $kgCO_2e/m^2$ GIA figure

This is to ensure fair and meaningful comparisons with projects of the same type, reflecting the efficiency of the asset's use.

⇒ Remember that when comparing options, the embodied carbon results should be normalised in the same way.

GIA is the area of a building measured to the internal face of the perimeter walls at each floor level[49].

NIA is the usable area within a building measured to the internal face of the perimeter walls at each floor level. This excludes, for example, stairwells, corridors and mechanical areas[49].

Roof areas that are not permanently covered are not included in GIA. Although this can make very low-rise construction more carbon intensive per GIA when compared to taller developments, this may reflect the efficiency of the development in terms of usable space throughout a year.

For **refurbishment projects**, the total embodied carbon should be divided by the GIA (and other functional equivalent) of the refurbished building including any new and existing floor area. This can be used to demonstrate the benefit of refurbishment over demolition and rebuild.

Now you will have values for the total embodied carbon (kgCO_2e) and normalised embodied carbon (e.g. in kgCO_2e/m^2 GIA) for, as a minimum, life cycle Modules A1–A5.

2.3.3 Sense check

Studies[50,51] have shown that business as usual construction for embodied carbon to practical completion (Modules A1–A5) for substructure plus superstructure structural elements typically ranges **between 150–400kgCO_2e/m^2**.

Where your project sits relative to this range will be influenced by a number of variables that affect material quantities, in addition to the carbon factors chosen. These include, but are not limited to: basement size; architectural form; requirement for transfer structures; typical span; number of storeys; building use (loading requirements); framing and floor type; ground conditions and location in relation to natural hazards. It is therefore important to note any project-specific design considerations when reporting embodied carbon (Section 2.3.5 and Section 2.4). Refer to Section 2.3.7 to make sure your project is at the lowest end of the range of possible embodied carbon.

Publicly available information on embodied carbon of structures is very limited, so to improve this and our understanding of embodied carbon in our designs, all structural engineers should share their embodied carbon data with the industry (Section 2.4.1).

2.3.4 Uncertainty

Uncertainty must not deter you from undertaking embodied carbon calculations.

Calculations of embodied carbon incorporate uncertainty to varying degrees for each lifecycle stage/module, and at different design stages. Sources of uncertainty are:

- Material quantities, Q_i
- Embodied Carbon Factors, ECF_i, for materials and processes

At concept stages, you may be making assumptions about material quantities in addition to material specifications. The possible range of embodied carbon could be significant. As projects progress, material quantities will become more accurate as detailed design is undertaken. Similarly, increasing certainty around material specifications and specific product sourcing as projects progress will allow ECFs to move from generic values to specific values, thereby increasing the accuracy of your assessment. Be aware of the uncertainty in the data when reporting embodied carbon.

⇒ This uncertainty must not deter you from undertaking embodied carbon calculations. Instead, note in your reports and calculations the sources of uncertainty, and use the open reporting of data to help reduce it.

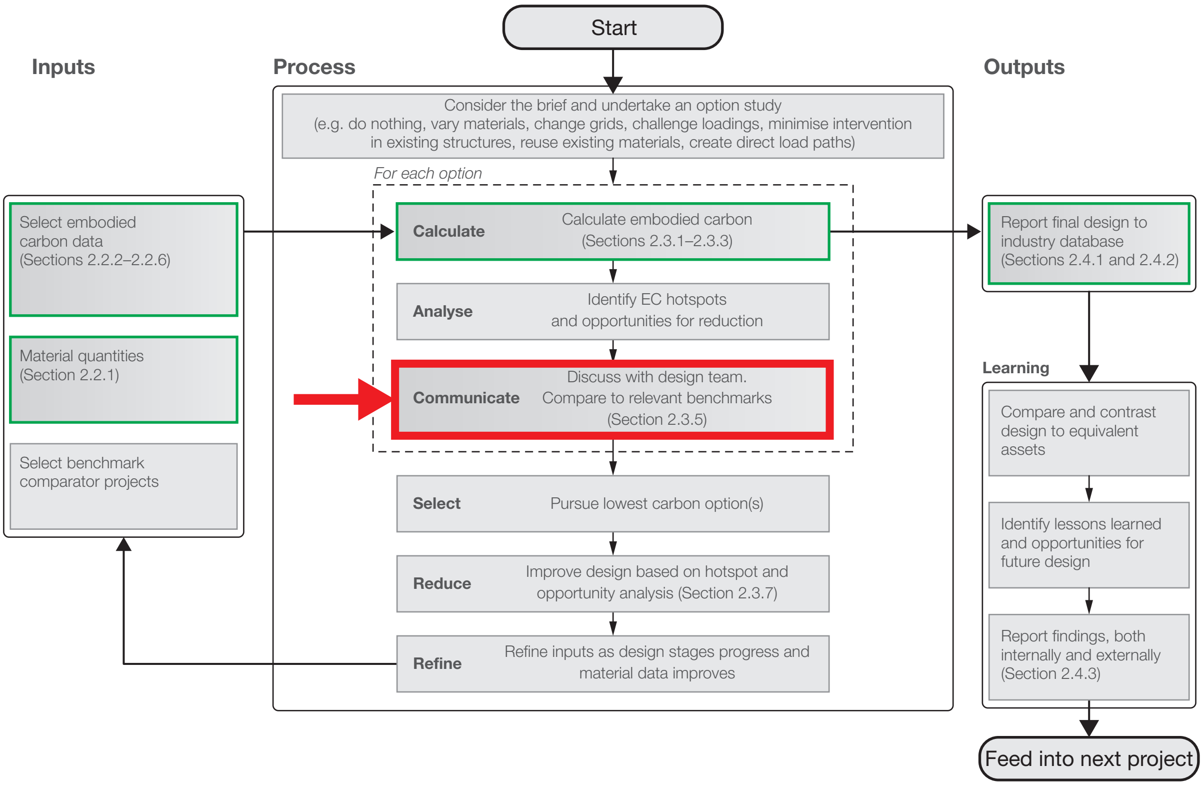
If you are comparing between options be cautious if one option has an obviously higher level of uncertainty than others, as this may lead to unfair comparisons.

A simple example is Module A5a — site activities. Eqn. (2.5) allows you to calculate A5a emissions based on a construction activities emissions factor related only to the total project cost. If every construction site recorded actual on-site electricity and fuel consumption and reported this as part of their as-built calculation, a more accurate picture of Module A5a could be created to improve the accuracy of future Module A5a calculations.

⇒ To reflect the level of uncertainty of your calculation you may wish to consider the number of significant figures you report your result to. This is to avoid unintentionally communicating that there is more accuracy than there is. One suggestion could be rounding to the closest tCO_2e, or the closest $kgCO_2e/m^2$. In addition, you could report the range of values, for example $100kCO_2e/m^2 \pm 5\%$.

2.3.5 Communicate and discuss embodied carbon

Figure 2.7: Calculating embodied carbon process overview (5)



It is essential that embodied carbon assessments inform the design process. Your calculations must be discussed with the design team, and form part of the agenda for design workshops.

⇒ You should regularly communicate and discuss results with your team. Include embodied carbon information in your stage reports, in client and design team presentations, and on your design drawings.

It is strongly recommended that your design team hosts an embodied carbon workshop at least at the start of:

- concept design (i.e. RIBA Stage 2)
- developed design (i.e. RIBA Stage 3)
- technical design (i.e. RIBA Stage 4)
- construction (i.e. RIBA Stage 5)

In these workshops:

- Discuss opportunities for embodied carbon reduction based on the embodied carbon assessment carried out during the previous work stage
- Create a strategy to implement these opportunities

Be ambitious and advocate to the client that the reduction strategies be implemented.

When discussing embodied carbon in any workshops, discussions or presentations with your project team, remember the following key points:

- **As a minimum, report Modules A1–A3, A4 and A5** (Section 2.1.1)
- For transparency, report module results separately as well as aggregated
- If reporting aggregated A–C results, report aggregated A1–A5 results to highlight the contribution of emissions up to practical completion. Section 2.1.1 shows the reasons for this
- Do not aggregate Module D results with Stage A–C results — report them separately
- If the scope of your calculation is A1–A5, and if using any timber products in your design, sequestration benefits should be reported separately alongside the total A1–A5 embodied carbon result (Section 2.2.2.1.5)
- Clearly state the units of normalisation, if applicable, e.g. m^2 GIA (Section 2.3.2)
- Clearly state the scope of calculation, addressing life cycle modules and elements assessed (Section 2.1)

This makes calculations transparent, easily understandable, easily comparable and allows the design team to keep a clear audit trail of the carbon parameters used in calculations.

Transparency of calculation scope is key to enabling meaningful comparisons and discussions with the design team.

⇒ If the scope of your calculation includes Stages A–C, it is recommended to report the A1–A5 result alongside the total A–C result on presentations and drawings. This helps to communicate the time dependency of emissions over the asset life cycle and highlight upfront emissions.

Figure 2.8 shows examples of clear presentation of embodied carbon calculation results for inclusion as a thumbnail on a drawing, sketch or presentation to the project team — one for a scope of A1–A5 (top) and one for a scope of A–C (bottom). It clearly states the calculation scope and units of normalisation.

Figure 2.8: Example of brief, clear and transparent presentation of A1–A5 embodied carbon (top) and A–C embodied carbon (bottom) for drawings, sketches or presentations†

A1 – A5: 178 $kgCO_2e/m^2$ GIA
Sequestration: –102
Substructure and superstructure

A – C: 212 $kgCO_2e/m^2$ GIA
A1–A5 (including sequestration): 76
Substructure and superstructure

† In line with the guidance given in Section 2.2.2.1.5, sequestration has been reported separately to A1–A5 where only A1–A5 is assessed. It is included within the totals reported where A–C is assessed.

For full transparency, an example of a more comprehensive range of assessment information, e.g. to be presented in design stage reports, is shown in Table 2.10.

Table 2.10: Comprehensive data for inclusion in an embodied carbon assessment report[5]

Assessment information	
Date of assessment	*e.g. 27/02/2021*
Project stage	*Design or construction stage at time of calculation*
Verified by	*Verifier name and organisation*
Project type	*e.g. New build or refurbishment of existing structure*
Project location	*Address, or provide the w3w location, e.g. https://w3w.co/mild.path.yards*
Date of project completion	*Estimate if not known, e.g. 01/05/2022 (estimated)*
Asset type	*e.g. Residential, public/civic, retail, office, road bridge, rail bridge, station, etc. For buildings, state planning use class*
Brief description	*e.g. No. storeys (below and above ground level), structural frame type, bridge structure, brief description of other notable features that have impacted project embodied carbon*
Size	*Functional units, e.g. GIA, NIA, volume, seating capacity, etc.*
Project design life	*Building default: 60 years, infrastructure default: 120 years*[5]
Modules included	*e.g. A1, A2, A3, A4, A5 (BS EN 15978)*[3]
Building elements included	*Infrastructure: N/A. Buildings: Table 1, e.g. 1.1 Substructure, 2.1 Frame, 2.2 Upper Floors, 2.3 Roof, 2.4 Stairs and ramps (structural elements only)*
Assumptions and scenarios	*List all assumptions and scenarios used in the assessment including brief justifications where appropriate*
Primary carbon factor source	*e.g. ICE database, EPDs*

2.3.5.1 Understanding interdependencies and whole life carbon impacts

Although A1–A5 is the minimum scope for a structural embodied carbon assessment, it is important to understand how different structural design solutions affect whole building carbon emissions over the lifetime of the building. This is achieved through coordination with the rest of the design team and an understanding of the interdependencies between the design of different building elements. For example, the interdependencies between the structural design and the following building elements should be checked:

- Mechanical systems — for Module B6 (operational energy)
- Facade systems — for Modules A1–A5, B4 (replacement) and B6
- Architectural finishes, e.g. ceilings and floors — for Modules A1–A5 and B4
- Fire protection — for Modules A1–A5 and B4

This approach will engage the whole design team in minimising whole building carbon emissions over the asset life cycle and avoid unintended consequences of minimising structural embodied carbon.

2.3.6 Calculation tools

The calculation of embodied carbon can become complicated where multiple materials, components and carbon factors are involved. Tools to assist in the calculation are available, and some of these are listed in Table 2.11. Note that some of these only cover Modules A1–A3. It is up to you to determine which tool best suits your needs.

Table 2.11: Selection of embodied carbon calculation tools (others available not listed here)

Type	Name	Scope	Applicable geographical regions	BIM plug-in functionality?	Link
Free at point of use	Beacon	A1–A3	USA	Yes	https://carbon.tips/beacon
	Embodied Carbon in Construction Calculator	A1–A3	USA	No	https://carbon.tips/ec3
	Hawkins\Brown Emission Reduction Toolkit (H\BERT)	A–D	UK	Yes	http://carbon.tips/hbert
	OneClick LCA Planetary	A1–A3	Many (incl. UK)	No	https://carbon.tips/planet
	eTool 'open use' subscription	A–D	All	No	https://etoolglobal.com/software/subscriptions
	RSSB Rail Carbon Tool	N/A	UK	No	https://carbon.tips/rssb
	Environment Agency – ERIC	A1–A5	UK	No	https://carbon.tips/cpt
Paid	OneClick LCA	A–D	All	Yes	https://carbon.tips/oneclick
	eTool	A–D	All	Yes	https://carbon.tips/etool
	Tally	A–D	USA	Yes	https://carbon.tips/tally
	ECCOlab	A–C	UK	No	https://carbon.tips/eccolab

Note: Check link to see which countries this tool is available in.

If there is no tool appropriate for your use, refer to Table 2.3 for a list of available A1–A3 carbon factors for the UK (see Appendix for other A1–A3 carbon factor data sources) for you to use to create your own calculation using the information presented in this guide.

2.3.7 Reducing embodied carbon

Embodied carbon calculations should be used to inform targeted design decisions that reduce carbon emissions, with an ambition to reduce whole life carbon of all assets to zero.

When considering a design, a suggested hierarchy for carbon reductions is illustrated in Figure 2.9 and Table 2.12, adapted from the PAS 2080[8] framework for integrating carbon reductions into the design process for infrastructure projects. LETI's *Embodied Carbon Primer*[9] also provides useful 'rules of thumb' embodied carbon reduction strategies.

Figure 2.9: Carbon reduction potential over time

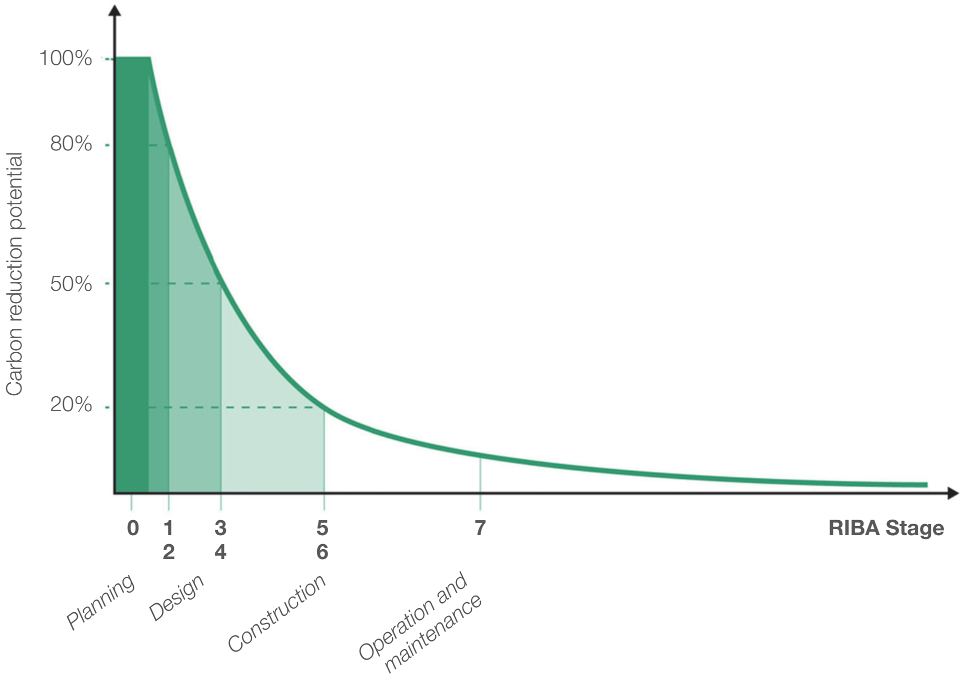


Table 2.12: A suggested hierarchy for carbon emissions reduction based on PAS 2080[8] hierarchy

Hierarchy	Description	Example design levers
Build nothing	Evaluate the basic need for an asset and consider whether any new construction is needed	Challenge the brief and propose alternatives. Improve utilisation of existing floor areas
Build less	Minimise demand for new construction: reuse, repurpose and refurbish existing assets and minimise extension sizes	Justify existing structures through analysis and surveying. Maximise usage efficiency of the existing asset and any new construction that may be required
Build clever	Make low carbon solutions (technologies, materials and products) your default option. Specify enough material and no more	Design to minimum loads (within code allowance), set realistic SLS criteria, set utilisation ratios to 1, reduce structural grids, spans and transfer structures, use efficient structural forms, low carbon material choices, low carbon material specifications and suppliers, reuse existing materials where possible
Build efficiently	Use of construction techniques to reduce resource consumption	Utilise temporary structures in the permanent condition, avoid over-ordering, do not allow possible site errors to alter design choices. Monitor construction emissions. Design to enable offsite manufacture to reduce waste on site

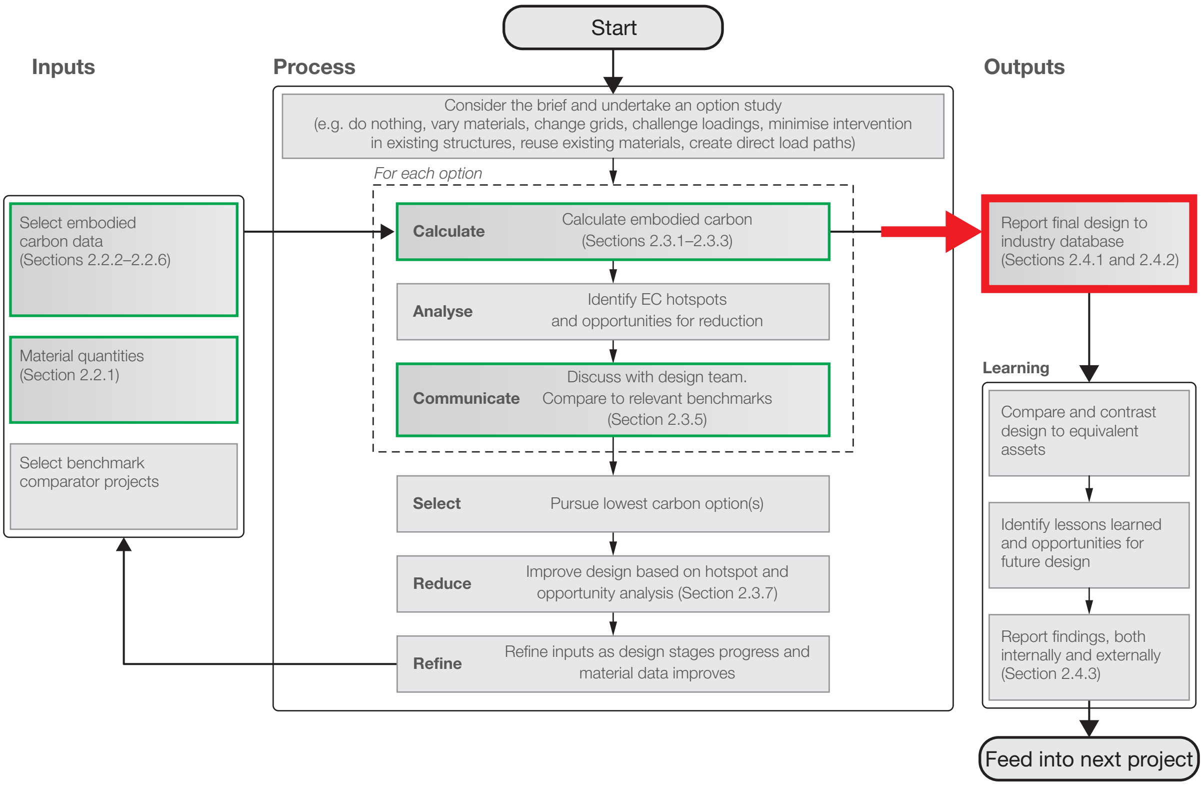
2.4 Outputs

Reporting project embodied carbon data to a publicly accessible database is vital to enable the development of benchmarks that can be used to inform embodied carbon targets for future legislation, and improve industry understanding of embodied carbon in the built environment.

A key tenet of resolving the climate emergency is a commitment to openly sharing data and best practice that can help us all to reach zero carbon. **It is therefore essential that embodied carbon data on all projects is reported in an open source and upfront manner.** This data will help to identify best practice, refine targets and identify opportunities in implementing significant embodied carbon reduction.

2.4.1 Reporting publicly

Figure 2.10: Calculating embodied carbon process overview (6)



In the UK we recommend making use of the *RICS Building Carbon Database*[52], as it is the only freely accessible industry wide project embodied carbon database in the UK. An easy way to upload information to the database is via the excel upload template spreadsheet which can be downloaded from the website.

⇒ It is strongly recommended that all embodied carbon calculation tools are adjusted to enable outputs in this format for quick uploading to the database.

Entries to the RICS database can be made anonymously and anyone can sign up. This public reporting should be made:

- At the end of the design stage (i.e. end of RIBA Stage 4)
- At the end of construction (based on as-built information)
- By a selected individual or group within your organisation to make the process of uploading data more efficient and consistent. This individual or group should take responsibility for verifying the data before uploading to the database, whether or not the database already has a data verification procedure in place

⇒ The results of the end of design stage calculation and the end of construction calculation are unlikely to be the same. Analyse the differences to help improve your understanding of embodied carbon in built structures for the next project you work on.

2.4.2 As-built calculation

The as-built calculation should be the most accurate measure of the true embodied carbon to practical completion (Modules A1–A5) of a project, as the specification and origin (for Modules A1–A3) of each product and material delivered to site, and therefore transportation mode and distance (for Module A4), will be known in detail. On-site material waste tracking and construction activity energy metering will inform a precise Module A5 value.

The calculation of an as-built carbon value relies on close cooperation with the main contractor through design and construction.

⇒ Wherever possible the main contractor's scope of work should include such monitoring and analysis. Site delivery and carbon tracking software[53] may be of use in such tracking activities.

2.4.3 Share case studies

Sharing case studies that highlight lessons learned in embodied carbon reduction is a key component of the climate emergency response. *The Structural Engineer* magazine welcomes case studies (large or small) on this topic, for consideration. Please send your case studies to tse@istructe.org.

3 Conclusions

This guide provides a common set of embodied carbon calculation principles for the structural engineering community to follow. The calculation of embodied carbon must now become a key part of every design process — to support our immediate need to reduce resource demand, increase reuse and recycling, and enable a circular economy.

While the calculation is simple, there remain many sources of uncertainty. The majority of our built assets have not been subjected to whole life carbon assessments, and so we currently have relatively little data on what current practice is achieving. Yet we must not be deterred from calculating embodied carbon because of uncertainty of carbon factors. Instead, through widespread measurement and open reporting of our calculation, we will collectively be able to reduce this uncertainty and reduce our climate impact.

As this information is generated, our ability to set reduction targets and benchmarks will improve. The measurement and reporting of embodied carbon data thus create a virtuous circle that reduces our uncertainty around what good design looks like and helps all design teams to improve their climate emergency response.

The Institution of Structural Engineers recognises the importance of addressing the climate emergency. The climate emergency declaration[54] recognises the importance of a swift response from structural engineering, and signatories seek to:

- Raise awareness of the climate and biodiversity emergencies and the urgent need for action amongst our clients, collaborators and supply chains
- Advocate for faster change in our industry towards regenerative design practices and a higher Governmental funding priority to support this
- Establish climate and biodiversity mitigation principles as a key measure of our industry's success: demonstrated through awards, prizes and listings
- Share knowledge and research to that end on an open source basis
- Evaluate all new projects against the aspiration to contribute positively to mitigating climate breakdown and encourage our clients to adopt this approach
- Upgrade existing buildings for extended use as a more carbon efficient alternative to demolition and new build whenever there is a viable choice
- Include life cycle costing, whole life carbon modelling and post occupancy evaluation as part of the basic scope of work, to reduce both embodied and operational resource use
- Adopt more regenerative design principles in practice, with the aim of providing structural engineering design that achieves the standard of net zero carbon
- Collaborate with clients, architects, engineers and contractors to further reduce construction waste
- Accelerate the shift to low embodied carbon materials in all our work
- Minimise wasteful use of resources in our structural engineering design, both in quantum and in detail

We hope that every structural engineering practice operating in the UK will join us in making this commitment. Visit www.istructe.org/structural-engineers-declare to find out how your company can sign up.

Appendix: Carbon factor databases

Carbon data can be obtained from a variety of sources. Table A.1 provides a list of such sources, based on publications from the EU Level(s) project[55]. Designers working in the UK are recommended to use the data provided in this guide, and the ICE database[15] for any A1–A3 carbon factors not covered.

If there is a body of carbon factor data for a specific country that is not referenced here, please go to https://carbon.tips/database and provide the information to be included in the next revision.

Table A.1: Life cycle assessment material/product carbon factor databases

Region	Database	Notes	Link
Europe			
UK	ICE database	Wide ranging material database covering Modules A1–A3	https://carbon.tips/ice3
UK	BRE Verified BS EN 15804 EPD	EPDs for specific products, with a range of modules	https://carbon.tips/breEPD
UK	BRE IMPACT	350 BS EN 15804-compliant datasets modelled in SimaPro	https://carbon.tips/umx
Europe	European Aluminium EPD Programme	EPDs for specific aluminium products, with a range of modules	https://carbon.tips/lca8
France	Environmental and health reference data for building construction products	EPDs for a range of building construction products, in French	https://carbon.tips/lca33
Germany	Oekobaudat	EPDs for a range of building products	https://carbon.tips/lca15
Germany	IBU	EPDs for specific products, in German. Requires registration	https://carbon.tips/lca17
Italy	EPD Italy	EPDs for specific products	https://carbon.tips/lca19
Norway	EPD Norge	EPDs for specific products	https://carbon.tips/lca18
Spain	DAP construcción	EPDs for specific products	https://carbon.tips/lca21
Sweden	International EPD	EPDs for specific products	https://carbon.tips/lca22
Switzerland	Ecoinvent	Paid database	https://carbon.tips/lca23

Table A.1: *Continued*

Region	Database	Notes	Link
North America			
Canada	CSA EPD	EPDs for specific products, some not available for immediate download	https://carbon.tips/lca2
Canada	CRMD	Requires registration. Small number of carbon emission data points	https://carbon.tips/lca3
USA	ASTM EPD	EPDs for specific products	https://carbon.tips/lca4
USA	EC3	EPDs for specific products	https://carbon.tips/4hv
Asia			
Turkey	EPD Turkey	EPDs for specific products	https://carbon.tips/lca27
Australia/Oceania			
Australia, New Zealand	Australasian EPD	EPDs for specific products	https://carbon.tips/lca29
New Zealand	Branz CO2NSTRUCT	Calculation sheet, using data from specific EPDs along with general databases	https://carbon.tips/lca34
South America			
Latin America	EPD Latin America	EPDs for specific products	https://carbon.tips/lca31

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How to calculate embodied carbon

This guide provides a common set of embodied carbon calculation principles for the structural engineering community to follow. The imperative to achieve net zero carbon by 2050 must change the way we practice — and calculating carbon is a key part of this.

Calculating embodied carbon in the same rigorous way across all designs will allow meaningful comparisons to be made between structural schemes, developing our understanding of embodied carbon as well as how we can most effectively reach net zero carbon. This guidance is equally applicable to infrastructure and building projects.

References to embodied carbon data and guidance are UK-focused. Where the authors are aware of such information from other countries, it is referenced in the Appendix. This document is aligned with *BS EN 15978*, *BS EN 15804* and RICS Professional Statement *Whole life carbon assessment for the built environment*. The guidance also supports the sustainability related core tasks in *The Structural Plan of Work 2020*.

The Institution of
StructuralEngineers

The Institution of Structural Engineers
International HQ
47–58 Bastwick Street
London, EC1V 3PS
United Kingdom

T: +44 (0)20 7235 4535
E: mail@istructe.org
W: www.istructe.org

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