WHAT COLOUR is YOUR BUILDING?

Measuring and reducing the energy and carbon footprint of buildings

David H. Clark

Appendix J

Materials data

www.whatcolourisyourbuilding.com

Appendix J: Materials data

The whole principle came from the idea that if you broke down everything you could think of that goes into riding a bike, and then improved it by 1%, you will get a significant increase when you put them all together.

Dave Brailsford,
Team GB cycling coach on his philosophy of the 'aggregation of marginal gains', BBC Breakfast, 8 August 2012.

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This appendix provides additional guidance to supplement the advice in Chapter 8 (Lower carbon materials), plus calculations and assumptions made in preparing the graphs used in the chapter.

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J1. ENVIRONMENTAL PRODUCT DECLARATIONS

An Environmental Product Declaration (EPD) is a clear and transparent certified factual statement of a product's environmental impact over its life cycle. It is not a rating or an ecolabel because it doesn't state whether something is good, bad or indifferent: it simply provides the raw data to enable purchasers and specifiers to make informed decisions.

EPDs are created using internationally recognised standards and must be verified by an independent third party. There are two components: Life Cycle Assessment (undertaken in accordance with ISO 14040) and Product Category Rules (EN 15804 sets out the core rules for construction products in the EU). European EPDs for construction products provide data for a variety of impacts summarised in Table J.1.

Environmental impacts	Resource use
• Global warming • Ozone depletion • Acidification for soil and water • Eutrophication • Photochemical ozone creation • Depletion of abiotic resources-elements • Depletion of abiotic resources-fossil fuels	• Use of renewable primary energy (excluding renewable primary energy resources used as raw materials) • Use of renewable primary energy resources used as raw materials • Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials) • Use of non-renewable primary energy (excluding non-renewable primary energy resources used as raw materials) • Use of non-renewable primary energy resources used as raw materials • Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)
Waste categories	
• Hazardous waste disposed • Non-hazardous waste disposed • Radioactive waste disposed	• Use of secondary material • Use of renewable secondary fuels • Use of non-renewable secondary fuels
Output flows	
• Components for re-use • Materials for recycling • Materials for energy recovery • Exported energy	• Net use of fresh water

Table J.1 Environmental impact categories for EPDs (source: EN 15084)

In the UK, the publicly available standard PAS2050:2011 specifies requirements for the assessment of the life cycle greenhouse gas emissions of goods and services. This is not a full EPD as it only covers one environmental impact.

In the book *Full Product Transparency – cutting the fluff out of sustainability*, Ramon Arratia clearly sets out the reasons why we need to shift from corporate sustainability to product sustainability, and the central role EPDs will play in this. He notes that '*we have been tremendously innovative in coming up with fairly meaningless stuff that is easy and quick to implement, or that can deliver nice stories and marketing claims, but frighteningly ineffective at producing anything that will affect actual performance.*'[1]

The key message is that people buy products and services, not companies, and so they are what we should be measuring and trying to make more sustainable. When was the last time you read a company's corporate sustainability report? The majority of the environmental impact of most companies falls outside their in-house operations:

- **Interface** – around 68% of the impact of carpet is associated with the production of raw materials, primarily nylon yarn. Only 10% is due to in-house operations.
- **Apple** – 61% of Apple's carbon footprint comes from outsourced manufacturing and the use of raw materials and 30% is due to consumers using their products. Only 2% comes from their own offices and facilities.
- **Cars** – 90% of the environmental impact is associated with the fuel consumed when driving cars.

Companies that focus only on the impact of their own operations, rather than the impact of their product or service, are probably missing the majority of their environmental and social impacts. For example, there is no point in having the world's greenest car manufacturing facility (winning lots of awards and ratings) if it is producing inefficient, gas-guzzling cars.

The use of robust, transparent EPDs, which cover the whole life cycle impacts of products, will force companies to focus on their real impacts, which in turn will drive innovation and competition in the supply chain. Voluntary approaches rarely transform markets, and so at some stage in the future, it will probably become necessary to introduce legislation for companies to provide EPDs. This is not a 'big stretch'. Food companies have to provide nutritional labelling (which is a similar concept), and the EU Construction Products Regulation 2011 requires manufacturers to draw up a declaration of performance and apply CE marking to any of their construction products covered by a harmonised European standard as of 1 July 2013.[2]

As Ramon neatly concludes: *'a new world based on LCAs and EPDs can take us away from the past decade of corporate responsibility fluff and towards a more practical era where companies make real social and environmental gains that are based on hard facts.'* It's hard to disagree.

ECOLABELS

Ecolabelling is a voluntary method of environmental performance certification that identifies the overall, proven environmental performance of a product or service within a specific product/service category. The easier an ecolabel is to obtain, the bigger its market share and the more revenue it generates, which can raise issues regarding robustness and extent of scope. The most credible ecolabels are based on life cycle considerations, and are awarded by an impartial third party after confirmation that they meet environmental leadership criteria. ISO14024 lists the guiding principles for Type 1 ecolabels. Refer to www.globalecolabelling.net for further details.

Examples of ecolabels include the EU's Ecolabel (www.ecolabel.eu), Good Environmental Choice Australia (www.geca.org.au), Germany's Blue Angel (www.blauer-engel.de), Green Seal (www.greenseal.org), Canada's EcoLogo (www.ecologo.org) and the Nordic Ecolabel (www.svanen.se). Will the widespread use of EPDs eventually make ecolabels redundant?

J2. REFURBISH OR REPLACE?

A major refurbishment can be undertaken with varying degrees of intervention:

- Strip back to the structure and façade (shell) and replace all building services and internal finishes.
- Strip back to base structure, replacing all or part of the façade.

The decision to refurbish an existing building, and the level of intervention required to improve its performance, requires many factors to be taken into account:

- Does the existing building (or do parts of the building) have heritage or cultural value that makes its preservation important?
- Is the existing structure (or parts of the structure) suitable for the intended use or can it be practically adapted (altered/repaired) for this use?
- What is the estimated design life before and after refurbishment for each component (structure, façade and services)? This will determine if they should be kept as found, upgraded or replaced.
- Will refurbishing the building save time and cost compared to new build?
- Can the existing building be made energy efficient?
- Can the existing building provide the required quality of indoor environment (comfort, daylight, acoustics and air quality)?
- How will the refurbished building respond to the potential impacts of future climate change – increased wind loads and more severe weather events?

If the building is to be demolished, then consider whether it is possible to reuse discrete structural components and maximise the segregation of demolition materials to simplify recycling (refer to section J14 on waste).

J3. REDUCING THE EMBODIED CARBON OF STRUCTURES

Chapter 8 provided some examples of how to reduce the embodied carbon (ECO_2) of structures:

- Avoiding overdesign.
- Design for durability and flexibility.
- Design for dismantling and reuse.
- Specifying lower carbon versions of materials.

Further guidance on the first three is given below. The options for lower carbon materials were discussed in Chapter 8 (refer also to sections J5 onwards for further details).

J3.1 Avoiding overdesign

Structural engineers use safety factors when designing the various elements in a building: footings, floor slabs, beams, columns, walls, retaining walls and bracing. This is necessary, as the consequences of failure (or excessive deflections/movement) can be severe – but overdesigning structural elements (or applying additional safety factors such as higher floor load allowances) can be wasteful of materials. Avoiding overdesign is the first step to reducing embodied carbon, irrespective of which material is used, as this reduces the volume of materials and/or the strength grade of material required. Higher strength materials typically have higher embodied carbon, but may require less material to be used.

The efficient design of steel beams is discussed in more detail in Section J6. A quirk of accounting for carbon storage in timber is that overdesigning timber elements reduces the calculated embodied carbon of a building. This is why carbon alone shouldn't be used to guide design decisions, and other environmental issues (such as the use of natural resources) must be considered, and common sense also applied.

J3.2 Durability and flexibility

The whole life carbon footprint is based on the expected life span of the structure. The following can be considered to extend this:

- What is the design life of the structure? Can it be extended by considering more durable materials?
- How flexible is the structure for future uses and loads? (But an appropriate balance between flexibility and overdesign needs to be found).
- Is there sufficient capacity in footings, columns and stability elements to allow vertical extension in the future (again noting the balance with overdesigning)?
- Is there enough floor to ceiling height for potential future uses?
- Internal cross bracing can reduce future flexibility.
- What is the impact of future climate change on the durability of the structure (e.g. increased extreme wind events and driving rain, flooding and foundation subsidence)?

J3.3 Designing structures for dismantling and reuse

In 2010, 47.4 million tonnes (mt) of waste was produced in the UK due to construction and demolition activities (excluding excavation), down from 58 mt in 2008.[3] Of this, 34.8 mt (73%) was used as aggregate, 7.2 mt (15%) was sent to waste transfer/treatment centres, and 5.3 mt (12%) ended up on landfill.

It is preferable to reuse high grade structural elements when a structure comes to the end of its life, rather than converting them into lower grade materials (known as 'downcycling'). To increase the potential for structural elements to be reused, the building should be designed so that it can be easily dismantled into discrete components. Issues to consider include:

- Steel (and precast) elements should be permanently marked with details of their strength grade.
- Can the structure be layered into easily replaceable elements? (For example, pre-fabricated composite elements comprising structure, insulation and inner skin are only as durable as the weakest link, requiring the whole element to be replaced).
- Components should be mechanically fixed instead of attached using adhesives (or welding) so that they can be more easily disassembled.
- Softer mortars should be used in masonry to simplify reuse of whole bricks.
- Jointing details should be standardised where possible.
- It should be specified that prefabricated components are clearly labelled, that shop drawings show design capacities and materials used, and that records of all shop drawings are kept on site.

J4. STEEL VERSUS CONCRETE STRUCTURES – AND THE WINNER IS…

The biggest challenge with embodied carbon is getting consistent results, as there is currently no industry consensus on which methodology or ECO_2 emission factors to use. New international standards will help to improve this,[4] but in something as complex as life cycle assessment, the values from different studies are unlikely to ever be easily comparable.

Perhaps this doesn't really matter, as there are currently no building regulations setting limits for embodied carbon – although this may change in the future. Instead of being overly concerned with absolute values, embodied carbon assessments should be used to compare the relative impact of options to identify where the biggest reductions can be made during design and construction.

To illustrate why the values should be treated as relative, not absolute, Figure J.1 shows the embodied carbon from different studies for two typical suspended floor systems: composite slab on steel frame, and concrete slab on concrete frame.[5] The data was sourced from:

- Steel Construction Industry – Eaton & Amato, 1998.
- Sustainable Concrete Architecture – David Bennett, RIBA Publishing, 2010.
- British Constructional Steelwork Association – Target Zero Office study, 2011.
- IStructE research paper – Concrete Centre / Arup, 2012.
- Cundall R&D project, 2013.

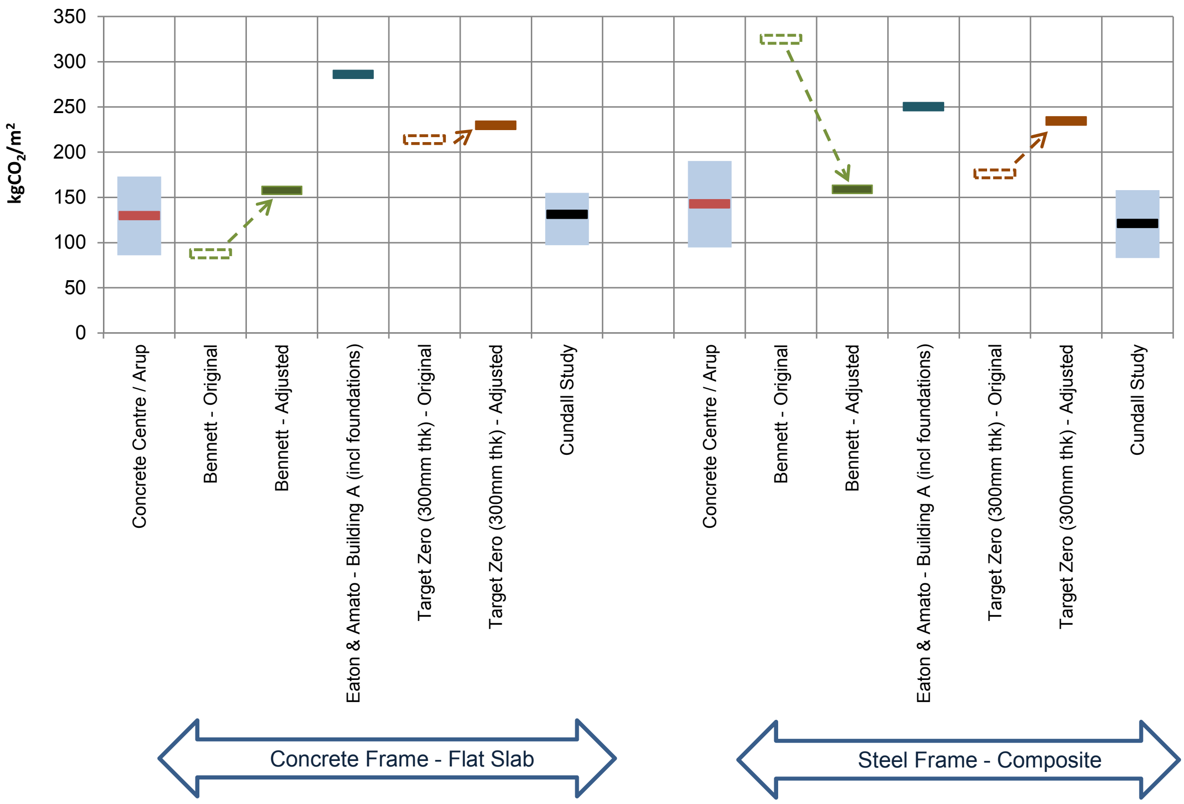

Fig J.1 **Comparison of embodied carbon values ("cradle to site") for steel and concrete superstructure**

Please note that this is not a scientific comparison, and does not attempt to state which values should be used. Instead, the aim is to highlight the wide range of results from different studies of similar structures. The values, except for Eaton & Amato, exclude substructure. For simple pad footings, this can be equivalent to 15% of the superstructure for concrete frames and 10% for steel frames (which are lighter).[6] The additional embodied carbon for basements and ground floor slabs would be similar for both types of structure.

After making some simple adjustments of the steel and concrete ECO_2 factors used in a couple of the studies (unadjusted values are shown dotted in Figure J.1), there appears to be little difference between an efficient steel framed structure and an efficient concrete structure.

J5. CONCRETE

J5.1 Embodied carbon reduction examples in Chapter 8

Figure 8.2 in Chapter 8 was based on the data in Table J.2 for a hypothetical 10 storey concrete framed building (Building X). This was adapted from data taken from a bill of quantities for a real 10 storey office building with a gross internal area of 9,250 m^2. All concrete mixes were assumed to have 15% fly ash and 85% Portland cement. Table J.3 shows the reduction in the floor slab alone.

	Volume of concrete (m^3)	% of concrete	Weight of concrete (kg)	Grade of concrete		ECO_2 factor ($kgCO_2e/kg$)		ECO_2 (tCO_2e)		ECO_2 ($kgCO_2e/m^2$)	
				Over design	Lower carbon design	Typical	Lower carbon design	Typical	Lower carbon design	Typical	Lower carbon design
Sub-structure	851	16%	2,086	28/35	25/30	0.138	0.13	288	271	29	27
Ground slab	440	9%	1,078	32/40	28/35	0.152	0.138	164	149	16	15
Upper floors	3076	60%	7,537	32/40	28/35	0.152	0.138	1,146	1,040	115	104
Columns	208	4%	509	32/40	32/40	0.152	0.152	77	77	8	8
Core walls	490	9%	1,200	32/40	32/40	0.152	0.152	182	182	18	18
Stairs	95	2%	233	32/40	32/40	0.152	0.152	35	35	4	4
Total	**5160**		**12,642**					**1,892**	**1,755**	**189**	**176**
Saving in concrete mix only									*7%*		
Reinforcement								488	488	20%	21%
Formwork								90	90	4%	4%
Total								**2,470**	**2,332**		
Total saving in reinforced concrete									*6%*		

Table J.2 Estimate of concrete structure embodied carbon for Building X for typical and low carbon design

Floor slab concrete grade	tCO_2e			
	Concrete	Reinforcement	Formwork	**Total**
28/35 (with 15% fly ash)	1,040	238	58	**1,336**
32/40 (with 15% fly ash)	1,146	238	58	**1,442**
Increase in CO_2e	*10%*			***8%***

Table J.3 Reduction in embodied carbon for Building X floor slab due to change in strength grade

Fig 8.3 in Chapter 8 was based on the data in Table J.4.

	Weight of concrete (m^3)	Grade of concrete	ECO_2 ($kgCO_2e/m^2$)				
			100% PC	15% fly ash	30% fly ash	25% ggbs	50% ggbs
Sub-structure	2,086	25/30	292	271	240	231	169
Ground Slab	1,078	28/35	160	149	134	128	95
Upper Floors	7,537	28/35	1,115	1,040	935	897	663
Columns	509	32/40	83	77	69	68	51
Core Walls	1,200	32/40	196	182	163	160	120
Stairs	233	32/40	38	35	32	31	23
Total for concrete	**12,642**		**1,883**	**1,755**	**1,572**	**1,515**	**1,121**
Reinforcement			488				
Formwork			90				
Total			**2,461**	**2,332**	**2,149**	**2,092**	**1,699**
ECO_2 saving compared to 100% PC				*5%*	*13%*	*15%*	*31%*

Table J.4 **Reduction in embodied carbon for Building X due to changes in cement mixes**

J5.2 Reducing embodied carbon through admixtures

The technical guidance note *Admixtures and Sustainable Concrete* by A. Minson and I. Berrie, published in The Structural Engineer, January 2013, provides a worked example to show how the use of water reducing admixtures can reduce the cement content:

- Strength requirement = C32/40, exposure = XC3/4, cover = 35 mm.
- A normal water reducing admixture (WRA) can reduce cement content by about 30 kg/m^3, giving a 5 to 8% saving in ECO_2 of the concrete.
- A high range water reducing admixture (HRWRA) can reduce cement content by a further 30 kg/m^3, giving a 10 to 15% saving in ECO_2 of the concrete.
- The total reduction cannot be realised for all cement types as the minimum cement content cannot be reduced below 260 kg/m^3 (BS8500-1 Table A.4).

J5.3 Embodied carbon savings on the London 2012 Olympics

The London 2012 Olympic venues delivered total concrete embodied carbon savings of 24,000 tCO_2.[7] This was achieved through efficient design, 32% cement replacement, super-plasticisers and on-site manufacture to reduce transportation. This represented a 24% saving compared with standard practice concrete, which has an 18% ggbs content.

J5.4 Other environmental considerations

The following steps can be considered to reduce the environmental impact of concrete:

- Request Environmental Product Declarations (EPDs) from suppliers of ready-mixed and precast concrete to site.
- Specify that returned (unused) ready-mix concrete is recycled.
- Utilise Recycled Aggregates (RA) – typically made from crushed masonry, these can form the coarse aggregate in low grade concrete.
- Utilise Recycled Concrete Aggregates (RCA) – typically made from crushed concrete, these form up to 20% of the coarse aggregate in concrete up to grade 40/50. Increasing RCA content to 100% reduces strength by up to 20% and stiffness by up to 10%.
- Consider where aggregates are sourced – transportation emissions v. environmental benefits of alternative aggregates.
- Specify non-toxic admixtures which have EPDs, and are preferably manufactured from sustainable raw materials.
- Specify that recycled water is used in the production of concrete.
- Specify low Volatile Organic Compound (VOC) off-gassing limits for curing compounds, sealants, membranes and coatings applied to concrete.
- Use void formers, spacers and bar chairs made from recycled materials.
- Specify that any steel or polypropylene fibres used in concrete mixes are made from recycled materials.
- Specify that where timber formwork is used, it is either reused timber or Forest Stewardship Council (FSC) certified (or equivalent).

J5.5 Alternatives to Portland cement

Various alternatives to Portland cement-based concrete can be used in some applications. These alternative materials, some of which are still under development, include:[8]

- Geopolymeric cements (e.g. Zeobond, Geo-Blue Crete).
- Low energy CSA-belite cements.
- Cements based on magnesium oxide derived from carbonates or from silicates (e.g. Eco-cement, Novacem).
- 'Eco-cement' based on municipal solid waste incinerator ash (MSWIA).
- Thermoplastic carbon-based cements (e.g. C-Fix cement).
- Existing fly ash heaps converted into cements and aggregates (e.g. RockTron).
- Cements using ground waste glass (e.g. ConGlassCrete).

J6. STEEL

J6.1 Recycled or recyclable - the impact on ECO_2 values

Figure J.2 shows the global flow of steel in 2008 from its source as ore or scrap (left) through the production system to the end use products purchased by customers.[9] End of life scrap metal makes up 15% of the total 1,568 million tonnes (mt) of raw materials used to produce 1,040 mt of steel used by consumers. The construction industry uses over half of this (583 mt), with 109 mt used for reinforcing steel in concrete and 109 mt for structural steel.

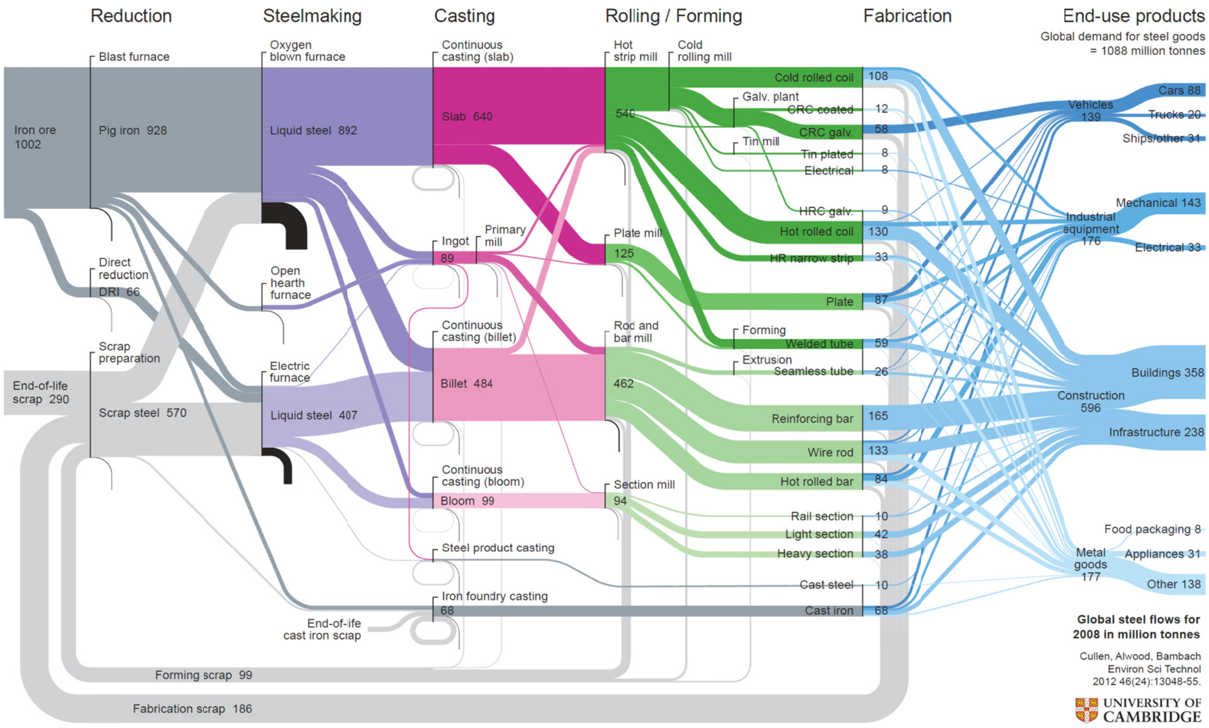

Fig J.2 Global flow of steel from production to end use (source: Cullen, Allwood et al)

Metals with a recycled content, such as steel and aluminium, have a lower embodied energy than metals produced from virgin ores. At the end of its life in a building, the metal is usually recycled. In the life cycle assessment of a building, you can't take both of these benefits into account. If you claim the CO_2 saving for recycling the metal then the purchaser of the recycled steel can't also assume this same CO_2 benefit because that would be 'double counting'. Figure J.3 shows the three options of accounting for steel recycling in a life cycle assessment:[10]

- **Recycled content** – no benefit for recyclability at the end of life (which may occur 60+ years in the future)
- **Substitution method** – the benefit of creating recycled material (its recyclability) is allocated at the end of life
- **50:50 method** – take half the benefit of recycled content (during construction) and recyclability (end of life)

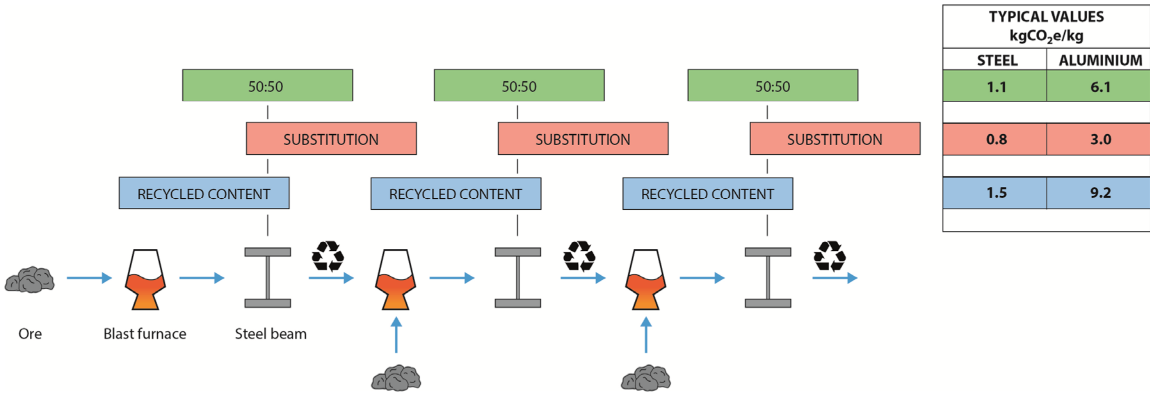

Fig J.3 **Different ECO_2 factors depending on method (diagram adapted from data in ICE v2)**

In cradle-to-gate databases, the only method that can really be used is recycled content, as this reflects the CO_2 emissions necessary to produce the material at the time of construction.

J6.2 What is the right ECO_2 factor for steel?

Steel has a wide range of published CO_2e emission factors compared to concrete. Table J.5 illustrates the dilemma facing anyone in 2013 undertaking an embodied carbon assessment to compare steel and concrete structures. Since the carbon factors vary significantly, it is hoped that the introduction of international standards will establish the methodology to use, which would avoid people cherry picking values to support a particular material preference.

$kgCO_2$/kg of steel	Source of ECO_2 factor
1.01	Target Zero publications in 2011 and 2012
1.53	Typical UK/EU steel, Inventory of Carbon & Energy v2, University of Bath
1.77	Embodied CO_2 of structural frames, S. Kaethner (Arup) & J. Burridge (Concrete Centre), The Structural Engineer, May 2012
2.11	CESMM3 – Carbon & Price Book 2011, Institution of Civil Engineers
2.12	Typical rest of world steel, ICE v2
2.47	DEFRA Greenhouse Reporting Guidelines 2012 – Table 14a for Construction Metals (assuming 59% recycled content and 41% primary production).

Table J.5 **Selection of ECO_2 factors for structural steel**

Figure J.3 illustrates the impact that these different factors can have on the ECO_2 assessment of a steel versus concrete framed building (based on the Cundall study referenced in Figure J.1).[11] As stated in Section J4, there doesn't appear to be a significant difference between steel structures and concrete structures if reasonable factors are used. In this book, the ICE v2 value for typical UK steel (1.53 $kgCO_2e$/kg) has been adopted, which is conservative compared to most of the published factors, but not as low as the factor used in the Target Zero studies (funded by Tata Steel and the British Constructional Steelwork Association).

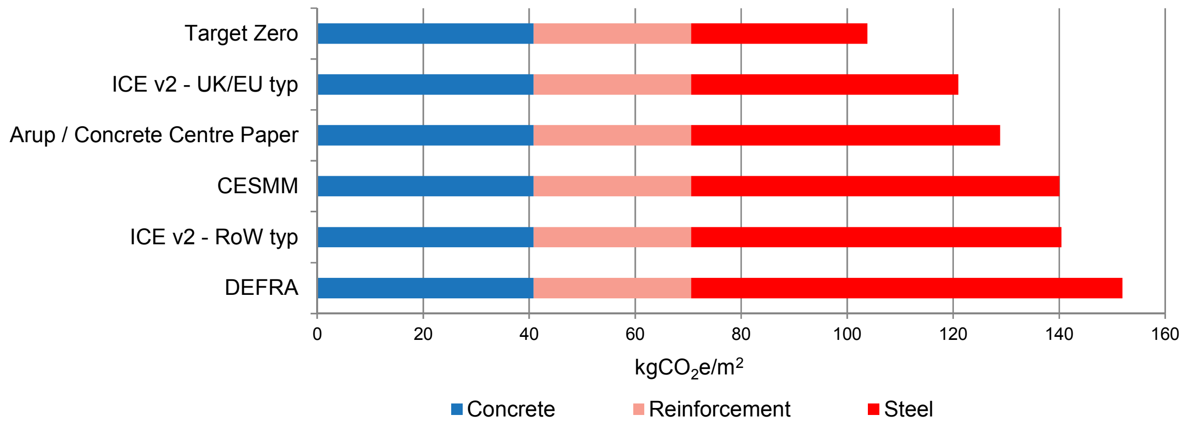

Fig J.4 Comparison of embodied carbon for a steel framed structure using different steel factors

J6.4 The utilisation of steel beams in buildings

To reduce the embodied carbon of a steel framed building (irrespective of the ECO_2 factor adopted) requires the weight of steel used in the building to be reduced. The typical design process for a steel beam is as follows:

- Calculate the loads on the beam.
- Determine the minimum beam size based on a variety of different criteria, including:
  - allowable deflection (to avoid cracking in finishes)
  - strength in bending and shear
  - axial tension and compression (usually for bracing members and columns)
  - lateral torsional buckling
  - combinations of the above.
- Select a standard steel section size which meets all of these requirements.

The efficiency with which a selected steel beam size is meeting the design criteria can be expressed using the utilisation ratio:

$$\text{Utilisation ratio} = \frac{\text{Actual performance value}}{\text{Max allowable performance value}}$$

For example, if deflection is the governing criterion for the sizing of a particular beam, then the governing utilisation ratio would be actual design deflection (in mm) divided by the maximum permitted deflection (e.g. beam span (mm) / 200). The optimum utilisation ratio for an individual beam is 100%.

On a typical floor plate, there will be a variety of beams with different loads and lengths, including primary and secondary floor beams (similar to bearers and joists in timber flooring), perimeter beams (supporting floor and cladding), bracing members for lateral stability, and trimming beams around penetrations. While most steelwork frames are designed in computer software, which calculates the design loads, criteria and sizing for every unique member, it has been standard practice for many years to standardise steel member sizes:

'… avoid individual design of every beam and every column length, in an attempt to achieve least weight. Only rarely does this achieve lowest cost.' The economics of steelwork design, FH Needham, 1977.

For a variety of reasons discussed later, the utilisation ratio of 100% is not practically achievable for every beam. However, it might be reasonable to assume that, with all the software and automated fabrication systems available, the average design efficiency of the steelwork in a steel framed building would be at least 75%. The reality is that many buildings will likely achieve utilisations much lower than this value, although further research is needed to confirm this as most structural engineers do not report the average utilisation of their designs.

Figure J.5 shows a potential idealised distribution curve for steel design utilisation ratios in a building. The kick at the lower end reflects the steel framing elements such as ties, which carry very little load but are necessary to hold the framing together (e.g. for stability during construction).

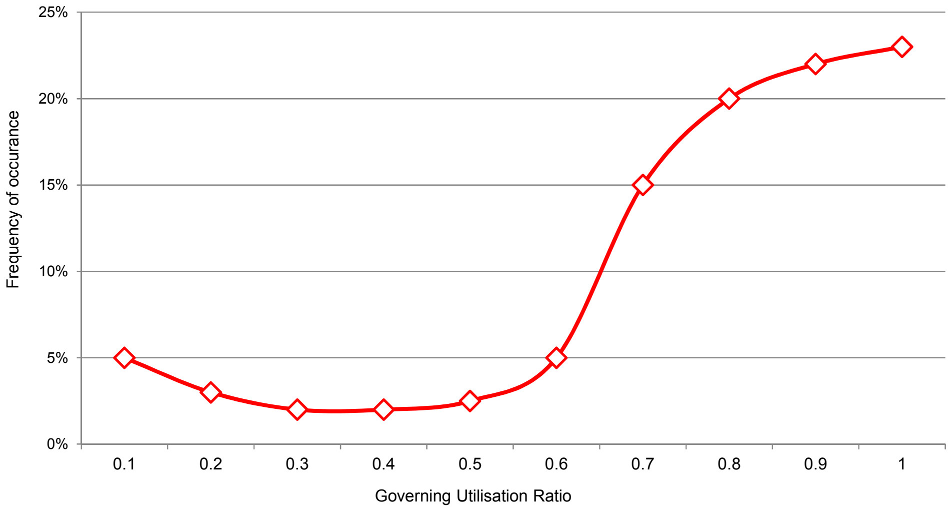

Fig J.5 Potential idealised distribution of governing utilisation ratio in a steel framed buildings

A perfect utilisation ratio of 100% is not achievable in a building for a variety of reasons, including the following:

- The nearest standardised section size might be larger than the minimum required.
- The beam depth might need to be increased to simplify the connection details at the ends or to allow penetrations through the web for building services.
- The optimum steel section might have a long lead in time which would delay the construction programme.
- The connection of shear studs for composite steel decking slabs may require a larger flange width than the optimum design beam size.

- Some conservatism is required because the steelwork frame is often designed or fabricated prior to the completion of the architectural and services design.
- The steelwork might be visible and standardised beam depths might be more aesthetically pleasing (and allow standardised fixing of services and finishes from the beams).
- Other criteria might also affect design, such as vibration, robustness and earthquake detailing.
- There isn't time or available fees to design every unique beam and connection detail, so similar beams are grouped together and designed for the worst case scenario.

At the time this book was written, the WellMet team at the University of Cambridge was undertaking research on design utilisation of steel framed buildings, including discussions with fabricators and designers on the implications of increasing the number of unique beams on a floor plate.[12]

Research is also underway on the practicalities of tailoring beam section profiles to suit the actual design requirements, instead of picking the nearest fit from a book of standard sections. Options include:

- Creating bespoke sections by welding plates together.
- Welding plates to the flanges or webs of standard sections.
- Fish-belly steel beams (horizontal upper flange and curved lower flange).

Most structural analysis software will provide the governing utilisation ratio for individual steel members, based on the design criteria established by the engineer. It would be useful if the software companies also added a function to calculate the average utilisation ratio for the whole building frame (both by number of elements and weighted average), so that engineers can report this and compare them against an appropriate benchmark. Until more research is undertaken, the author suggests that an interim benchmark of 75% could be adopted.

J7. TIMBER

J7.1 Whole of life timber emissions

Calculation of the embodied carbon and the potential carbon sequestration (storage) benefit of timber structures is open to interpretation and requires assumptions regarding the end of life of the timber to be made. Figure J.6 shows some published values for CO_2 emissions at various stages of the life cycle for 1 tonne of felled wood, of which 29% ends up as timber in a building.[13] This is just one of many different estimates for CO_2 emissions associated with timber, and its inclusion here is to illustrate the life cycle issues with timber – not to imply that these are the right figures to use in embodied carbon assessments.

Table J.6 summarises the whole life CO_2 emissions for different end-of-life scenarios using the values from Figure J.6. For example, if sustainably managed forest is used to produce the timber, and at the end of its life it goes to landfill with no methane capture for biogas, then the emissions are [(–1516 + 425 + 39 + 1076) / 293 =] 0.09 $kgCO_2/kg$ of timber product. This ignores any timescale impacts on global warming associated with when the CO_2 is stored (growing cycle) and released (disposal), which could occur over a 100+ year time period.[14]

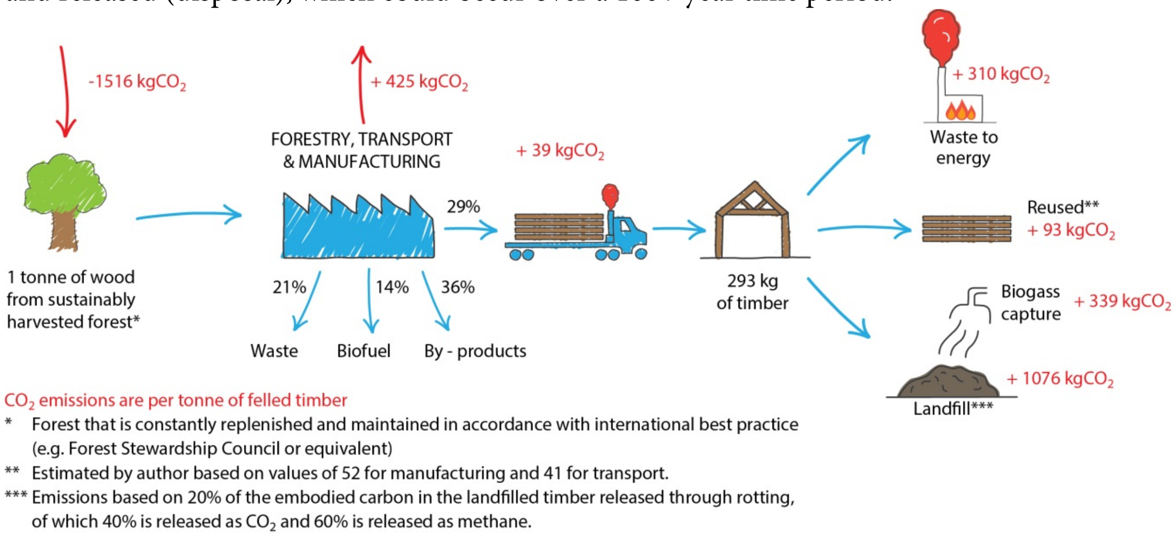

Fig J.6 **Example CO_2 emissions during the life cycle of timber (adapted from D. Weight, 2012)**

Timber at end of life	$kgCO_2/kg$ of timber product
Landfill (no methane capture)[15]	+ 0.09
Landfill with biogas capture	– 2.43
Waste to energy	– 2.52
Reused	– 3.59

Table J.6 **Example timber ECO_2 factors for different scenarios to compare end-of-life scenarios (adapted from D. Weight, 2012)**

The cradle-to-gate value for timber products (excluding carbon sequestration) from the Inventory of Carbon and Energy database is lower, at 0.72 $kgCO_2/kg$, compared to [425/293 =] 1.45 $kgCO_2/kg$ calculated from Figure J.6.

In 2013, the author assisted a contractor with the evaluation of a building which was required to achieve a 'net zero carbon' footprint in under 25 years, including both operating and embodied energy. The building developer established a set of rules for using carbon sequestered in the timber frame and cladding as part of their strategy, but ignored the potential CO_2e emissions at the end of the building's life in their methodology. Four major timber suppliers were asked to supply Environmental Product Declarations or other third party verified data for their engineered timber product so that the embodied carbon could be determined. Table J.7 summarises the data that was supplied.

Supplier	3rd party certified EPD	kgCO₂e/kg						
		Cradle to gate (Modules A1 – A3)			End of life (Module D)			**TOTAL**
		Carbon storage	Process	**Total**	Combust in CHP	Substitute fossil fuel	**Total**	
A	Yes	-1.49	0.26	**-1.22**	1.61	-0.73	**0.88**	**-0.34**
B	Yes	-1.84	0.12	**-1.72**	1.6	-0.69	**0.91**	**-0.81**
C	No	-1.83	0	**-1.83**	-	-	**-**	**-**
D	Yes	-2.01	0.71	**-1.3**	2.03	-1.0	**1.04**	**-0.26**
Value from Figure J.6		*-5.2*	*1.45*	***-3.75***	-	-	***1.05***	***-2.7***

Table J.7 ECO_2 values for cross laminated timber products

There was a wide variation in cradle-to-gate values, but all were much lower than the value suggested in Figure J.6. Explaining the variation in carbon storage and process emissions requires a detailed review of the EPDs – and even then the reasons are not obvious. The end of life values in the EPDs were based on timber being sent to waste-to-energy power stations. The value for the substitution of fossil fuels (i.e. the 'avoided burden' by using the timber product as a fuel) is usually calculated based on the country in which the timber product is manufactured. If it is used and disposed of in another country then the values could be different, as the fossil fuel mix being displaced will be different (refer to Appendix B for electricity emission factors in different countries to illustrate the wide variations in the carbon intensity of electricity generation). Different assumptions lead to different results, making it hard to compare materials.

European standard EN 16485, which at the time of writing was under development, will provide specific rules for EPDs for timber and timber products. The use of EPDs is essential to make informed decisions. For example, Supplier C in Table J.7 stated that they used wood chips and offcuts to power ovens to dry timber and to generate electricity, and therefore their process emissions were zero. They didn't provide an EPD with third party certification, however, or identify which standards their calculations were based on. Should their values be believed?

While a lot is understood, significantly more research and debate is required to confirm which ECO_2 values should be used for timber in embodied carbon assessments – the variations are huge – and how carbon sequestration should be accounted for. Given the current uncertainties, ECO_2 values for timber should be used for guidance rather than treated as absolute. Section J7.2 provides guidance on how to reduce the environmental impact of using timber, irrespective of the reasons why the material was selected.

J7.2 Sustainable use of timber

To reduce its environmental impact, consider the following steps when using timber in buildings:

- Use recycled timbers if available.
- Specify that the timber supplier must provide a third party certified Environmental Product Declaration (EPD) prepared in accordance with international or European standards (e.g. EN 15978).
- Avoid the use of tropical timber whenever possible.
- Specify and source new timber from certified sustainable sources, such as Forest Stewardship Council (FSC).*
- Minimise the use of timber preservatives through careful detailing (to keep the timber dry) and specifying naturally durable timber species.
- Avoid using toxic timber preservative treatments.
- Specify Composite Wood Products (e.g. plywood, particleboard, mdf) with low formaldehyde content (Class E0 standard).

* Other certification schemes recognised by DEFRA's Central Point of Expertise on Timber (CPET) are not as credible as FSC, according to both WWF and Greenpeace. These include: the Canadian Standards Association (CSA), the Programme for the Endorsement of Forest Certification Schemes (PEFC) and the North American Sustainable Forest Initiative (SFI).

J7.3 End of life data for timber in the UK

TRADA's Wood Information Sheet *Recovering and minimising wood waste* WIS 2/3-59, published in May 2012, contains the following statistics related to annual wood waste in the UK:

- 4 million tonnes of waste generated:
  - 25% - construction
  - 26% - demolition
  - 9% - joinery and furniture
  - 13% - municipal
  - 27% - packaging.
- 2.8 million tonnes recycled (70%):
  - 40% used to produce chipboard
  - 38% exploited as biomass fuel
  - remainder used for animal bedding, horticultural products and surfacing materials.
- 1.2 million tonnes landfilled (30%):
  - still scope for improvement
  - much less than the 8 million tonnes TRADA estimated in 2008.

The figures demonstrate that significant progress has been made since the mid-1990s when less than 4% of wood waste was recycled.

J8. MASONRY

J8.1 Example calculation for embodied carbon of brick and block walls

Table 8.7 in Chapter 8 was based on the calculations shown in Tables J.8 and J.9.

	ECO_2 ($kgCO_2$/kg)	Height (m)	Width (m)	Depth (m)	Area (m^2)	Volume (m^3)	Density (kg/m^3)	% void	Weight of unit (kg)
Brick	0.24	0.065	0.215	0.1025	0.0140	0.0014	1700	5%	2.3
Block	0.063	0.215	0.44	0.1	0.0946	0.0095	1400	0%	13.2

	Cement	Insulation	
Thickness	0.01	0.1	m
Density	1400	25	kg/m^3
ECO_2	0.156	1.35	$kgCO_2$/kg
ECO_2/m^2	-	3	$kgCO_2/m^2$

	Area of mortar (m^2)	Area with mortar (m^2)	ECO_2 total ($kgCO_2$)			Units per m^2	ECO_2 per m^2 ($kgCO_2/m^2$)		
			Unit	Mortar	Total		Unit	Mortar	Total
Brick	0.0029	0.0169	0.5552	0.0649	0.6201	59.3	32.9	3.8	36.7
Block	0.0067	0.1013	0.8344	0.1452	0.9796	9.9	8.2	1.4	9.7
Total							**41.1**	**5.3**	**46.4**
Allowance for waste on site (e.g. cutting bricks/blocks)							5%	10%	
Total (including waste)							**43.2**	**5.8**	**49.0**

Table J.8 Estimate of embodied carbon for a brick/block cavity wall (excluding insulation)

Thickness	0.2	m
Density	2400	kg/m^3
ECO_2	0.174	$kgCO_2$/kg
ECO_2/m^2	84	$kgCO_2/m^2$
Reinforcement	150	kg/m^3
Weight	30	kg/m^2
ECO_2	0.77	$kgCO_2$/kg
ECO_2/m^2	23	$kgCO_2/m^2$
Total	**107**	**$kgCO_2/m^2$**

Table J.9 Estimate of embodied carbon$_2$ for a 200 mm thick precast concrete wall (excluding insulation)

J9. GLAZING AND CURTAIN WALLING

J9.1 Embodied carbon in glass

In 2009, the global market demand for flat glass was 52 mt (million tonnes). Around 29 mt was for high quality float glass, 3 mt for sheet glass and 2 mt for rolled glass, with the remainder (approximately 19 mt) being lower quality float, produced mainly in China.[16] Four companies produce two thirds of the world's high quality float glass. 80% of the float glass produced globally was used in new or existing buildings. In 2010, China used approximately half of the world's flat glass.

Sand, limestone and soda ash are the principal virgin raw materials used to make glass, an energy-intensive process which requires a lot of heat. Re-melting waste glass uses 25% less energy than making glass from raw materials and can be used in the production of glass containers and fibreglass.[17]

There is likely to be a large variation in the embodied carbon of glass from different countries as it will depend on the fuel sources used and the energy efficiency of the manufacturing plants.

J9.2 Curtain walling calculation

Figure 8.6 in Chapter 8 was based on the calculations and assumptions shown in Table J.10.

Height of panel	4					
Panel width	3	mullions @ 1.5 m, 3 transoms				
Length of framing support	17					
	Glass	Aluminium glazing bar		Aluminium	Steel	Timber
Depth (m)	2.98	0.04		0.08	0.08	0.08
Width (m)	3.98	0.05		0.05	0.05	0.05
Thickness (mm)	14	4		4	2.5	n/a
Area (m^2)	11.8604	0.001		0.001	0.001	0.004
Length (m)	n/a	17		17	17	17
Volume (m^3)	0.1660456	0.011		0.017	0.011	0.068
Density (kg/m^3)	2500	2700		2700	7800	800
Weight (kg)	415.1	30.1		44.8	82.9	54.4
kgCO_2e/kg	1.35	9.16		9.16	1.53	0.59
kgCO_2e per panel	**560.4**	**275.8**		**410.4**	**126.8**	**32.1**
kgCO_2e *per m^2*	47	23		34	11	3
Total kgCO_2e/m^2				**104**	**80**	**72**
Reduction in façade ECO_2				*n/a*	*23%*	*30%*

Table J.10 **Calculation of embodied carbon for different façade mullion options**

J10. CARPET

Interface conducts Life Cycle Assessment (LCA) on the whole range of their carpet tile products. Figure J.7 shows a summary of impacts from an LCA for a 700 g carpet tile, assuming that the product goes to landfill at the end of life, no green energy is used during the life cycle, and the product lifetime (use) is 10 years.[18]

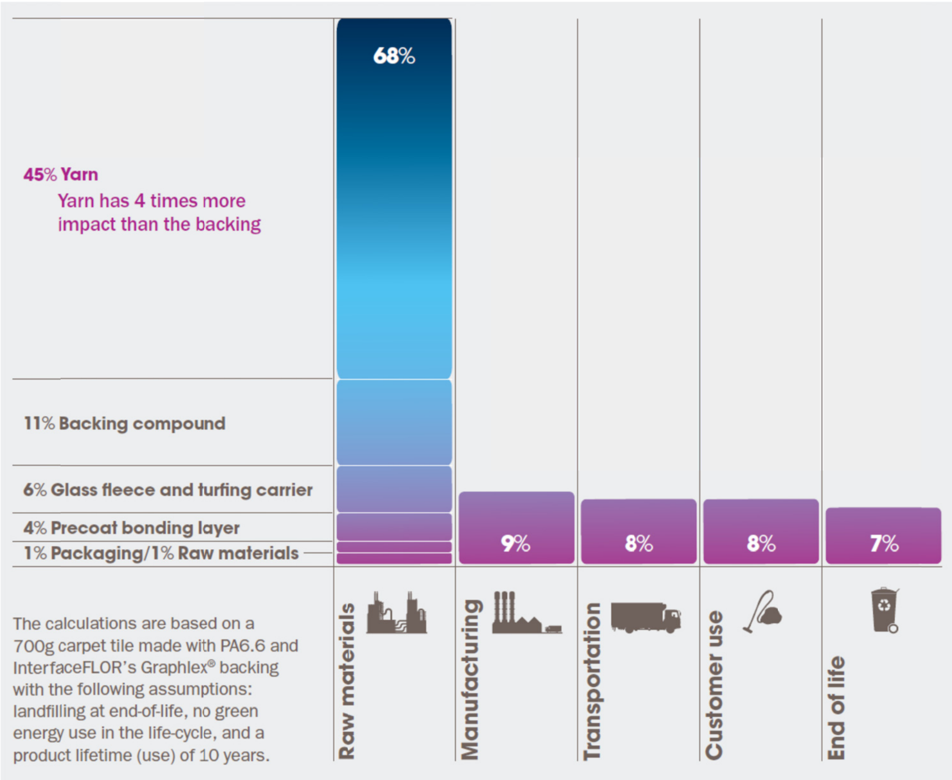

Fig J.7 **Summary of life cycle impacts from a carpet tile (source: Interface)**

The raw materials and processes needed to produce nylon yarn account for more than two thirds of the total impact, with nylon production accounting for almost half of the full life cycle impacts of a carpet tile. Therefore, to reduce the impact of a carpet tile, the focus needs to be on the yarn:

- Reduce the amount of yarn used per m^2.
- Increase yarn recycled content – which is less energy-intensive than virgin yarn.
- Create a smarter yarn – e.g. develop bio-based alternatives to nylon yarn.

Table J.11 shows the $kgCO_2/m^2$ for an Interface 600-700 g/m^2 solution dyed tufted carpet tile for three scenarios:[19]

1. 100% landfill.
2. 100% municipal waste incineration (MWI).
3. 100% recycling in the cement industry.

The cradle-to-gate value (A1 to A3) represents just over half of the embodied carbon of the whole life cycle (A to D) if the carpet tile goes to landfill or is incinerated in a waste-to-energy plant. If the carpet tile is recycled, the whole life cycle embodied carbon is approximately the same as the cradle-to-site factor (A1 to A5). What happens at the end of life is clearly critical when determining the embodied carbon of carpets.

The cradle-to-gate value for the carpet tile in Table J.11 of 7.38 $kgCO_2/m^2$ is less than the value given in Table 8.9 from Chapter 8 for an equivalent generic nylon carpet tile (13.7 $kgCO_2/m^2$). This shows the importance of using EPDs for specific products whenever possible in embodied carbon assessments instead of generic values. Asking suppliers to provide EPDs will encourage their wider uptake.

	Raw material supply, transport & manufacture	Transport	Construction-installation process	Use	Maintenance	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential	**TOTAL**
Scenario	A1-A3	A4	A5	B1	B2	C2	C3	C4	D	**A to D**
1	7.38	0.188	0.487	0.003	0.292	0.01	0	5.63	-0.254	**13.7**
2							0	8.38	-2.72	**14.0**
3							0.03	0	-0.453	**7.9**

Table J.11 **$kgCO_2/m^2$ for a 600-700 g/m^2 solution dyed tufted carpet tile (source: Interface)**

J11. FURNITURE

Figure 8.7 in Chapter 8 was based on the data in Table J.12, taken from *A Study Into The Feasibility Of Benchmarking Carbon Footprints Of Furniture Products* by the Furniture Industry Research Association in 2011.

Product	$kgCO_2$ per unit			No. of products evaluated
	Average	Min	Max	
Task chair	72	40	143	13
Visitor chair	36	9	81	19
1600mm x 1800mm rectangular desk	35	25	56	8
6 people bench desk	228	185	271	2
1600mm x 800mm wave desk	63	63	63	1
1600mm x 1200mm work station	45	45	45	1
Desk high pedestal	29	20	39	5
Bookcase	18	13	21	3
Tambour	50	38	62	2
Steel pedestal	44	44	44	1
Wooden filing cabinet	48	39	57	2
Cupboard	31	25	38	2
1000mm kitchen wall unit	25	16	32	5
500mm kitchen wall unit	18	10	31	9
1000mm drawer line unit	41	36	45	4
500mm drawer line unit	29	18	42	8
Full height base unit	17	12	21	4
1000mm storage unit	42	39	46	3
500mm storage unit	40	25	48	4
Worktops	26	20	33	4
Appliance housing	35	22	46	4
Base sink unit	22	22	22	1

Table J.12 ECO_2 data for furniture products (source: FIRA, 2011)

J12. EXTERNAL PAVING

J12.1 Comparison of pavement options

The comparison of pavement options in Figure 8.7 from Chapter 8 was based on the pavement details shown in Figure J.8.

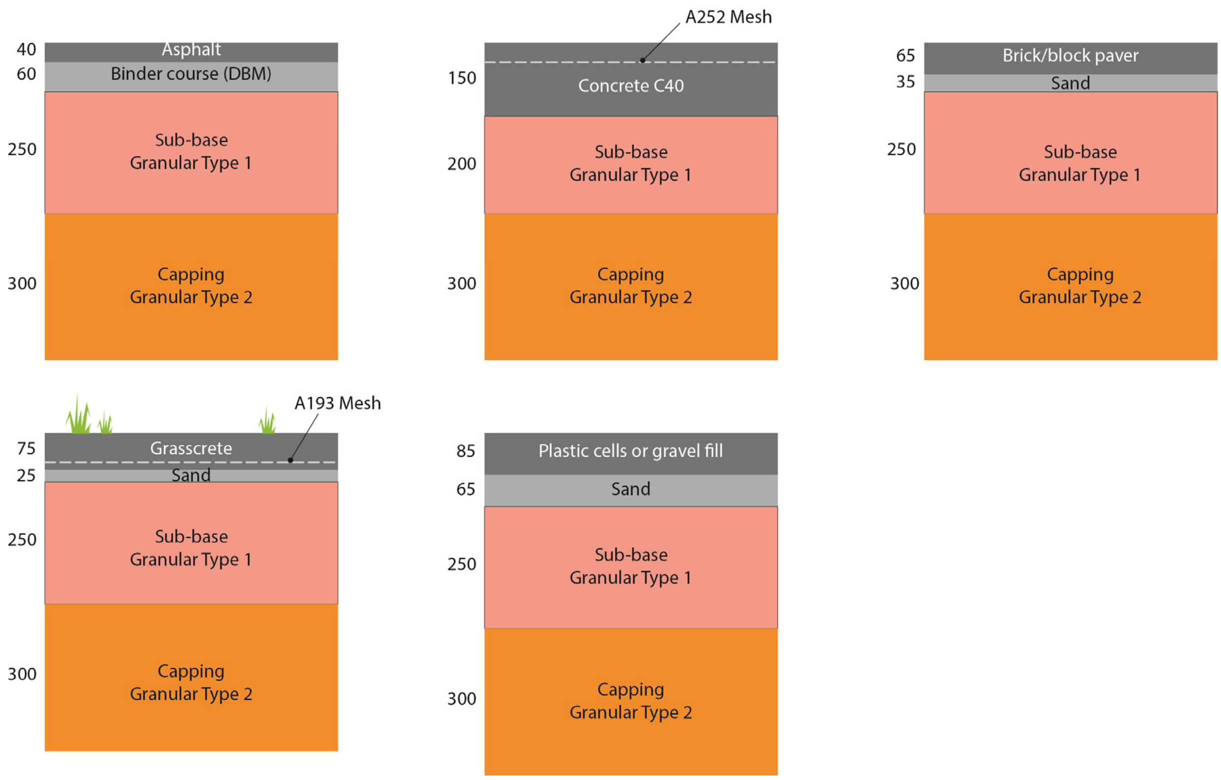

Fig J.8 Pavement comparison options

It was assumed that all materials were transported 50 km (with an ECO_2 factor of 0.241 kgCO_2 per km per tonne), except stabilised soils (reused on site) and concrete (average ready mix concrete travel distance in the UK is 10 km).[20]

J11.2 Options to strengthen subgrade

Figure J.9 shows three options for a standard asphalt pavement constructed on a weak subgrade. The ECO_2 values in Figure 8.8 in Chapter 8 were based on the following options:

- Excavate 300 mm of material and replace with imported granular fill.
- Use of a geotextile.
- Soil stabilisation to a depth of 300 mm and reuse of fill material on site:
  - 5% Portland cement stabilisation.
  - 5% lime stabilisation.
  - 4% fly ash + 1% lime stabilisation.

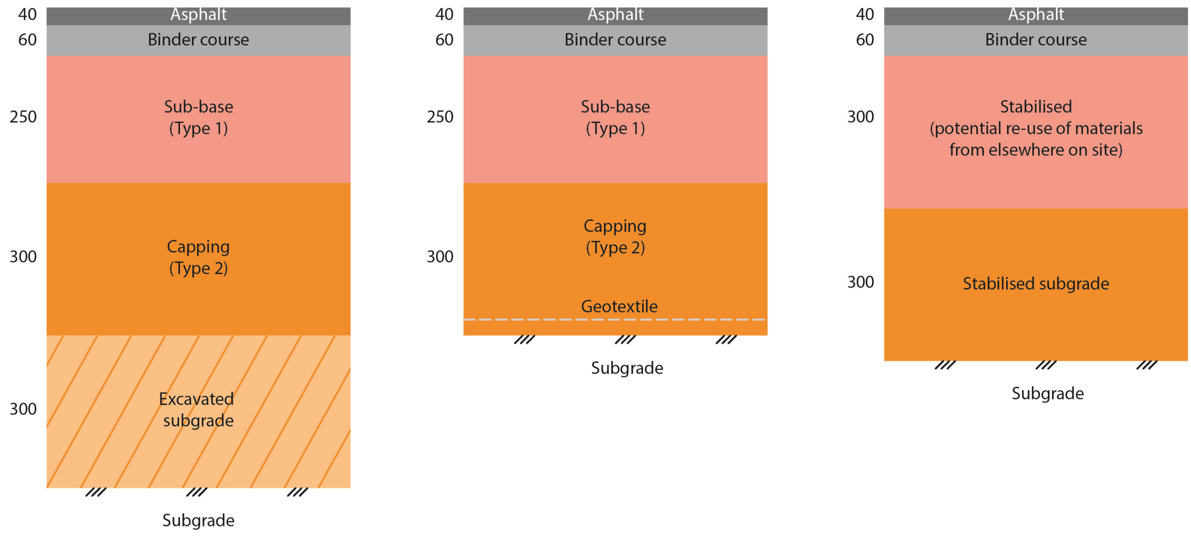

Fig J.9 **Subgrade improvement options**

The results of the analysis show that soil stabilisation using a fly ash mix, or ground strengthening using geotextiles, are the lowest embodied carbon solutions. Further environmental benefits of these two options are the reduction of waste to landfill (avoid excavating the subgrade) and, for soil stabilisation, a reduction in the consumption of natural resources if existing materials excavated elsewhere on site are available and suitable. Landfill tax, hazardous waste disposal charges and aggregate levies all support on-site retention and reuse of materials – embodied carbon is not the only environmental factor that should be considered.

Further guidance is available at:

- http://aggregain.wrap.org.uk/sustainability/index.html
- www.sustainabilityofhighways.org.uk/ – asphalt embodied CO_2 tool.

J13. CONSTRUCTION PROCESS

Table J.13 summarises some of the actions listed in the report *Carbon: reducing the footprint of the construction process.*[21]

Issue	Potential actions
Energy efficient site accommodation	Purchase / hire new site cabins and retrofit existing cabins to achieve high levels of energy efficiency including: • Good insulation, glazing and air tightness. • Efficient heating and lighting systems. • Motion sensors. • Metering of heat and electricity. • Master switch to turn off all appliances (e.g. computers). • Occupant awareness and behaviour change.
Efficient use of construction plant	Strategies to select and use construction plant and ancillary equipment efficiently include: • Choosing the right machine for the task – avoid inefficient oversized machines. • Selecting a plant that is more fuel efficient (and ask suppliers to provide consumption benchmarks). • Servicing the plant regularly and correctly. • Using sustainable low carbon fuels. • Operating the plant efficiently (e.g. minimising idling time and using appropriate power).
Earlier connection to the grid	To minimise the volume of diesel used for generators, seek to connect to the national electricity grid as soon as possible.
Good practice energy management on site	In addition to efficient site accommodation and plant: • Control generators to meet only current electricity needs. • Avoid unnecessary night time site and accommodation lighting. • Install energy efficient security and task lighting. • Establish effective server management for computers.
Onsite measurement, monitoring and targeting	Record and report all energy consumption on site, including electricity and fuels, and comply with relevant construction-specific measurement and reporting protocols (if they exist). State the boundary conditions (e.g. does data include sub-contractors' emissions?) Benchmark against other projects (use $kgCO_2e$ per m^2 of GIA) and make the information publicly available.
Fuel efficient freight driving and renewable transport fuels	Strategies for reducing the carbon impact of freight (delivering to site and taking materials away from the site) include: • Using more fuel efficient vehicles. • Reducing the amount (tonnes) of materials moved. • Reducing the distance travelled. • Using low carbon vehicle fuels. • Increasing the utilisation rate of vehicles. • Increasing driving efficiency through driver behaviour, speed limiters and/or other engine control units. * * *Drivers who have completed a one-day training course on average reduced fuel consumption by more than 10% without impacting on journey time.*

Construction consolidation centres	Consolidation centres receive bulk materials and products for multiple construction sites and then reload into delivery vehicles for 'just in time' delivery. They can improve the efficient flow of materials by: * • Ensuring departing delivery vehicles are fully loaded. • Maximising the reuse and recycling of materials and packaging at the centre. • Checking the quality and condition of goods arriving (avoiding the need for re-ordering and redelivery). • Providing elements of pre-assembly (e.g. hinges to doors). * *Data from the London Consolidation Centre demonstrates around 75% reduction in CO_2 emissions from 'last mile' deliveries into London construction sites.*
Renewable fuels	Generators and equipment are most commonly fuelled by diesel. The use of alternative biofuels could be considered. There are a number of issues associated with using biofuels in purpose built or existing equipment. Sharing experiences with other contractors will improve knowledge related to performance, reliability, equipment warranties, cost, OH&S, security of supply and other factors which can have an impact on the use of alternative fuels.
Reducing the transport of waste	Refer to Section J13 for guidance on reducing waste generated on site. Seek out regional materials exchange networks to redirect potential waste from waste facilities to on-site or local reuse.
Business travel fleet management and modal shift	Strategies to reduce domestic transport used by contractors include: • Promoting one hour Smarter Driving lessons for all staff members who have leased vehicles, access to company fuel cards or claim significant personal mileage (e.g. more than 5,000 miles a year).* • Allowing only passenger vehicles with A or B rated fuel economy labels to be provided as a company car. • Reducing domestic flights by shifting to rail travel and video conferencing. * *Data from the Energy Saving Trust shows that driver training can lead to fuel savings up to 15%.*
Good practice energy management of corporate offices	Refer to Chapters 6 and 7 for steps to reduce the carbon footprint of corporate offices.

Table J.13 Potential actions to reduce ECO_2 due to site activities (adapted from CPA report 006)

J13. WASTE

The UK Government's Waste & Resource Action Programme (WRAP) has produced a wealth of guidance on how to reduce waste in construction. This can be downloaded from www.wrap.org.uk/construction and includes various tools & templates, guidelines, quick wins, standard details and case studies.

Figure J.10 shows a summary of the processes from the WRAP publication *Achieving good practice Waste Minimisation and Management: Guidance for construction clients, design teams and contractors*.

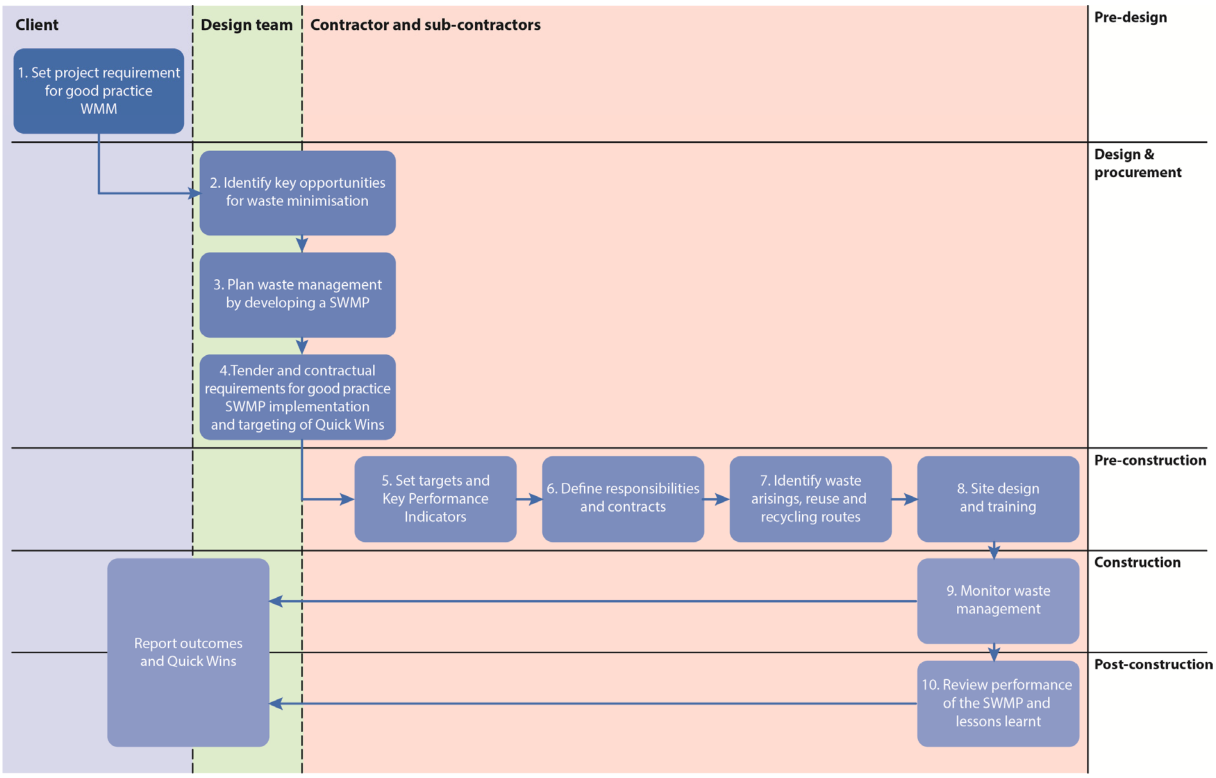

Fig J.10 Summary of WRAP process for good practice waste minimisation and management (source: WRAP)

The first step is establishing a project requirement for best practice waste minimisation and management. The following sample project brief wording is reproduced from the WRAP publication *Procurement requirements for reducing waste and using resources efficiently: Guidance for building and civil engineering project*. The percentage targets should be changed to suit each project.

Sample project brief wording

'Our design and construction project teams will be required to:

- Implement Site Waste Management Plans that comply with regulatory requirements throughout the design and construction period (where applicable) and include in such plans project-specific targets for waste recovery and reused and recycled content (below) and targets for waste reduction.

- Measure and report progress against the corporate KPIs for the quantity of waste produced and the quantity of waste sent to landfill (measured in tonnes per £100k construction value.
- Recover at least 70% of construction materials and aim to exceed 80%.
- Recover at least 80% of demolition, strip-out and excavation materials (where applicable) and aim to exceed 90%.
- Ensure that at least 15% of total material value derives from reused and recycled content in new construction, select the top opportunities to exceed this figure without increasing the cost of materials and report actual performance.

Project teams shall forecast waste quantities and reused and recycled content and set targets for waste reduction from an early design stage.

Before starting on site, the project team shall submit a copy of the Site Waste Management Plan, identifying the actions to be taken to reduce waste, increase the level of recovery, increase reused and recycled content, and quantify the resulting changes.

On completion of the Works, the project team shall submit a copy of the completed Site Waste Management Plan, reporting the forecast and actual performance for waste quantities, disposal routes and reused and recycled content used in construction.'

REDUCING WASTE IN THE CAR INDUSTRY

The European Commission End-of-Life Vehicle directive, introduced in 2000, placed responsibility on vehicle manufactures to take back and scrap cars in the future. The EU directive requires that 85% of a vehicle, measured by weight, is capable of recovery and reuse by the end of 2005. This rate rises to 95% by 2015.

When it was first proposed, it was met with anger by car manufacturers: '*Car makers say European Union plans to make them recycle old cars will cost them billions and push up the price of new vehicles. The proposed move has been condemned by manufacturers, and has run into opposition from German Chancellor Gerhard Schroeder.*'[22]

The story has changed over 12 years: '*We establish the basis for environmentally friendly and efficient reuse even before a new model enters production. By using recyclable synthetics, a reduced range of materials, and careful separation of different materials, BMW has ensured that vehicles can be recycled quickly and efficiently. As economically sound as it is environmentally friendly, it has placed the BMW Group among the leaders on the Dow Jones Sustainability Group Index, the world's most important list of sustainability-oriented companies.*'[23]

Figure L.1 in Appendix L provides a summary of this all too familiar scenario when new environmental legislation is proposed in an established industry.

Notes

All websites were accessed on 25 May 2013 unless noted otherwise. Information papers referenced are available to download from www.wholecarbonfootprint.com.

1. *Full Product Transparency – cutting the fluff out of sustainability*, Ramon Arratia, Dō Sustainability, 2012, www.dosustainability.com.

2. *Guidance Note on the Construction Products Regulation*, Version 2 - December 2012, Construction Products Association. www.constructionproducts.org.uk.

3. Data taken from www.defra.gov.uk/statistics/environment/waste/wrfg09-condem/. A further 30 mt of waste was generated by excavation activities, of which 7.3 mt was used as aggregate and the rest sent to landfill or exempt sites.

4. Refer to Information Paper 13 – Embodied carbon standards for further details.

5. Refer to Information Paper 31 – Embodied carbon of steel v concrete buildings for details and findings of the various studies, including how values were adjusted by the author to allow comparison in Figure J.1.

6. The Cundall R&D study showed an increase in pad footing size of around 67% for the concrete framed building compared to the steel building. This was equivalent to 7 $kgCO_2/m^2$ of GIA or 6% of the superstructure.

7. *The procurement and use of sustainable concrete on the Olympic Park*, Learning legacy: Lessons learned from the London 2012 Games construction project. http://learninglegacy.london2012.com/documents/pdfs/procurement-and-supply-chain-management/01-concrete-pscm.pdf

8. For more details, refer to *Sustainable Concrete Architecture* by David Bennett, RIBA Publishing 2010, and *Novel cements: low energy, low carbon cements*, Mineral Products Association (MPA), Cement Fact Sheet 12, March 2013. http://cement.mineralproducts.org/documents/FS_12_Novel_cements_low_energy_low_carbon_cements.pdf.

9. *Going on a metal diet – using less liquid metal to deliver the same services in order to save energy and carbon*, Allwood et al, University of Cambridge, 2011. WellMet2050 is investigating methods of meeting global carbon emissions targets for steel and aluminium by reconsidering the entire product lifecycle. The four main themes are: reuse without melting; less metal, same service; longer, more intense metal use; and supply chain compression. www.lcmp.eng.cam.ac.uk/wellmet2/introduction

10. Refer to Annex B of the *Embodied Carbon: The Inventory of Carbon & Energy (ICE)*, BSRIA Guide 10/2011 for a detailed discussion on how to account for metal recycling in embodied carbon assessments.

11. Refer to Information Paper 31 – Embodied carbon of steel v concrete buildings for further details.

12. Research project for WellMet 2050 project by Muiris C. Moynihan and Julian M. Allwood of the University of Cambridge. A paper is expected to be published in late 2013. Refer also to end note 9.

13. ECO_2 data is adapted from *Embodied through-life carbon dioxide equivalent assessment for timber products*, David H. Weight, Proceedings of the Institution of Civil Engineers, Energy 164, November 2011, Pages 167–182.

14. The life cycle emissions of carbon in timber are complex and assessment should consider issues related to how long it takes a new tree growing to absorb CO_2 and the eventual release of this CO_2 when the timber reaches the end of its life. Annex E of PAS 2050:2011 *Specification for the assessment of the life cycle greenhouse gas emissions of goods and services* provides guidance on calculating the weighted average impact of delayed emissions resulting from carbon storage. European standard EN 16449, which at the time of writing was under development, will provide a methodology to calculate sequestered carbon in timber.

15. Landfill gas emissions were based on the Weight paper (refer to end note 13). Landfill gas emissions

in the UK can be estimated using the GasSim tool developed for the Environment Agency. www.gassim.co.uk.

16. Pilkington and the Flat Glass Industry 2010, www.pilkington.com/resources/pfgi2010.pdf

17. www.britglass.org.uk/industry.

18. Taken from *Just the facts – how to choose the most sustainable products and what to ask the manufacturers* by Interface. www.interfaceflor.co.uk/web/sustainability/epd

19. Taken from EPD for *Modular carpet tiles tufted, PA 6 (> 75 % recycled content), 600-700 g/m², solution-dyed, Graphlex® backing system*. www.interfaceflor.in/web/in/sustainability/epd/certificates

20. The average delivery distance of ready-mixed concrete to the construction site in 2011 was 10 km, and 96 km for precast concrete products. The average delivery distance for all concrete was 35 km. Source: *Concrete Industry Sustainability Performance Report, 5th report: 2011 performance data*, published by MPA The Concrete Centre, on behalf of the Sustainable Concrete Forum. www.mineralproducts.org/sustainability/reports.html

21. *Carbon: Reducing the footprint of the construction process, July 2010, An Action Plan to reduce carbon emissions*, prepared by Joan Ko on behalf of the Strategic Forum for Construction and the Carbon Trust. Report 006 published by the Construction Products Association.

22. http://news.bbc.co.uk/1/hi/business/402518.stm

23. www.bmw.com/com/en/owners/service/recycling.html.