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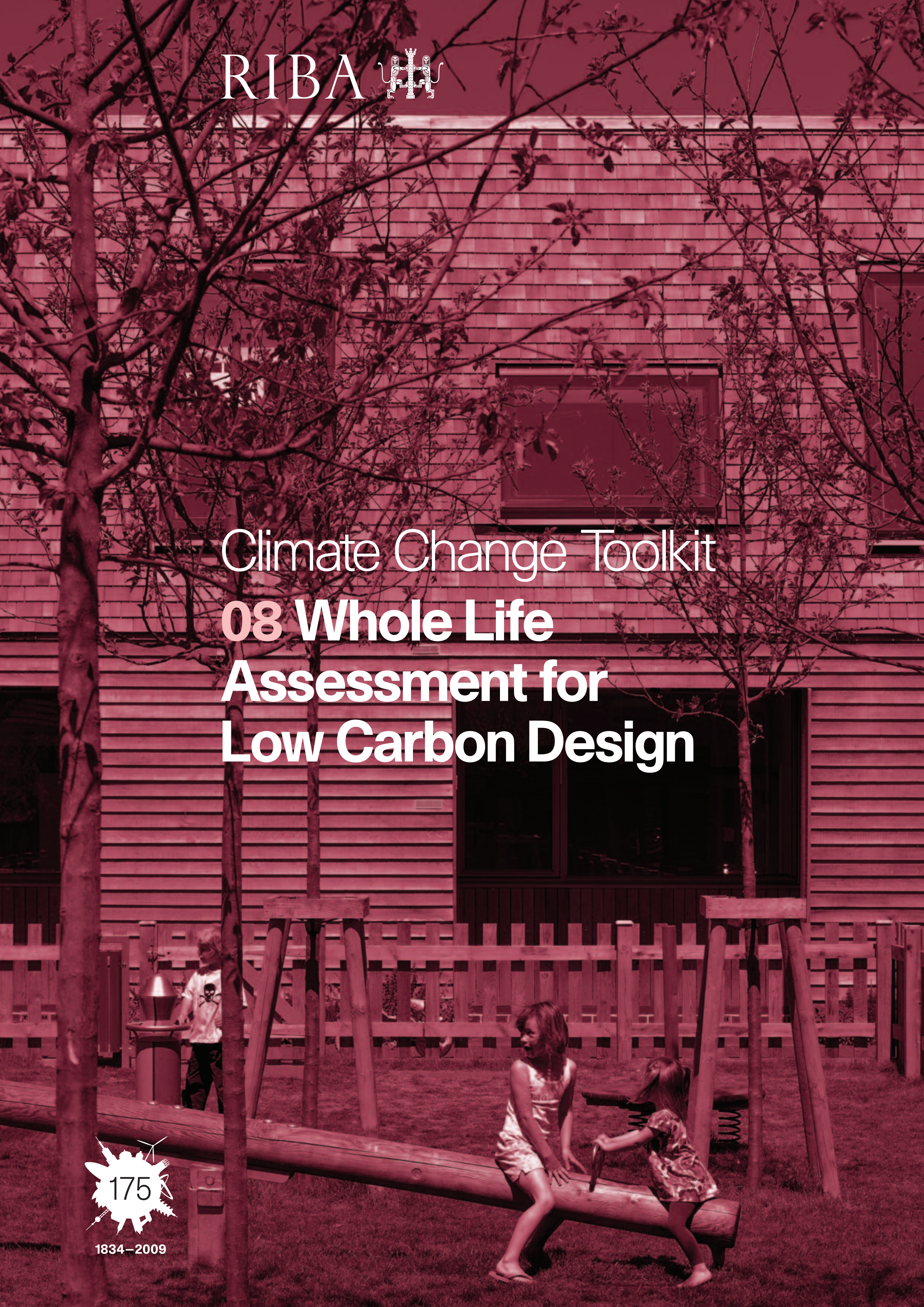

Climate Change Toolkit

08 Whole Life Assessment for Low Carbon Design

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Cover image Clay Field in Elmswell, Suffolk by Riches Hawley Mikhail Architects. The Clay Field project is an RIBA competition-winning scheme for Orwell Housing Association, The Suffolk Preservation Society and Elmswell Parish Council. The affordable housing project combines sustainable strategies for construction, lifetime energy use and landscape. Clay Field has been awarded Ecohomes 'Excellent'. The project is subject to post-occupancy evaluation by the Sustainability and Alternative Technologies Team at Buro Happold; results so far indicate that the performance of the project is living up to expectations, for instance CO_2 emissions to date equal 11.3 $kgCO_2/m^2$.
Photo Tim Crocker

About this Document

This is last of eight components of Climate Change Tools, a package of guidance developed by the RIBA to encourage architects to engage with the issue of climate change and to deliver low carbon new buildings and low carbon refurbishment of existing buildings.

This document provides an introduction to whole-life assessment, the types and sources of data required, methods of analysis, and a starter guide to self-assessment.

01 *Climate Change Briefing*

02 *Carbon Literacy Briefing*

03 *Principles of Low Carbon Design and Refurbishment*

04 *Low Carbon Standards and Assessment Methods*

05 *Low Carbon Design Tools*

06 *Skills for Low Carbon Buildings*

07 *Designing for Flood Risk*

08 *Whole Life Assessment for Low Carbon Design*

Each guide summarises its subject and provides links to other sources of more detailed information.

You can explore all of the RIBA Climate Change Tools at www.architecture.com/climatechange

Introduction

Climate change brought about by man-made emissions of greenhouse gases has been identified as the greatest challenge facing human society at the beginning of the twenty-first century.

There is an overwhelming scientific consensus that climate change is taking place as a consequence of man-made greenhouse gas emissions. Many of our day to day activities create emissions of greenhouse gases – running our buildings, traveling, extracting resources, manufacturing products.

A recent report by the United Nations Inter-governmental Panel on Climate Change (IPCC) confirms that global greenhouse gas emissions increased by 70% and carbon dioxide emissions by 80% between 1970 and 2004, in line with world-wide economic growth, and predicts that emissions will continue to increase over the next several decades[1].

The effects of climate change are complex. They include:

- Increased average temperatures
- Rising sea levels (because of the melting of glaciers and of polar ice caps)
- Increased precipitation
- More frequent extreme weather events.

Action to address climate change falls into two categories: mitigation policies are designed to reduce greenhouse gas emissions to slow down or stop climate change; adaptation policies are designed to adjust society to cope with climate changes that are already happening or are likely consequences of current GHG emissions.

Tackling climate change requires concerted and focused action. This will include reducing carbon dioxide emissions by changing the ways in which buildings are designed, constructed, managed and used. The broad principles of sustainability or sustainable development are complementary to the measures needed to mitigate climate change, but addressing climate change has emerged as a matter that must be tackled in its own right.

This briefing:

- Provides a definition of whole-life assessment
- Identifies different types and sources of data for inclusion in assessment
- Assesses methods of analysis for whole-life assessment and debates issues around risk, timescales and data quality
- Includes a self-assessment matrix which design teams can use to help get started on whole-life assessment
- Provides links to a wide range of websites, publications, policy documents and standards.

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[1] *Climate Change 2007: Mitigation of Climate Change*, Working Group III Contribution to the Fourth IPCC Assessment Report, UNIPCC, 2007

Whole Life Assessment: Key Points

Whole-life assessment is conceptually simple but can be difficult to apply, mainly because of data problems. With further development, data sources will no doubt get better, and new ideas like the shadow price of carbon and lifecycle options will make whole-life assessment more useful.

Meanwhile, you should press for a whole-life perspective in all design decision-making, using common sense, experience, and whole-life assessment as appropriate.

The following key points may be useful:

1. **Quantification of the embodied and current carbon dioxide CO_2 emissions associated with a design helps to indicate where to focus efforts to reduce CO_2 emissions.**
2. **Select design alternatives that generate large, certain or early reductions in CO_2 emissions, over those that generate weaker, uncertain or distant benefits.**
3. **Don't rely on detailed predictions or fine distinctions: whole-life assessment is imprecise so only big differences are credible.**
4. **Aim for robust design strategies that work well for a diversity of future scenarios, especially in situations of high uncertainty.**
5. **For elements where there are no opportunities for future upgrading, prioritise initial investment in building to a high specification to minimise CO_2 emissions.**
6. **For elements where there are opportunities for future upgrading, consider deferring initial investment and upgrading to higher specifications later.**
7. **Before investing resources in a CO_2 emissions-saving strategy, stand back and check that there isn't a completely different way of investing the resources to generate greater CO_2 emissions savings.**

What is Whole Life Assessment?

Buildings contribute to CO_2 (carbon dioxide) emissions throughout their life-cycle, so design to reduce CO_2 emissions should take a whole-life perspective.

To identify the most CO_2-efficient strategies, designers must compare design alternatives in terms of the CO_2 emissions from the initial construction, performance in use and disposal. This is whole-life assessment (see Figure 1).

The principle is simple, but you will need to use a systematic methodology. There may be trade-offs between design alternatives with, on the one hand, high emissions in initial construction but low emissions in service life and disposal and, on the other hand, others with lower emissions in construction but higher emissions in use.

A durable and efficient design often performs better over the life-cycle, despite higher emissions in construction. But not always – investing more doesn't necessarily give good value.

You should aim to avoid under-investment, when whole-life emissions are higher than necessary because of low initial specification. It is equally important to avoid over-investment, when emissions in construction are too high to be offset by reduced emissions in use.

This Climate Change Tool describes data sources and methods of analysis for whole-life assessment, and also gives worked examples. It concentrates on environmentally-based life cycle assessment, but also gives some information about money-based whole-life costing.

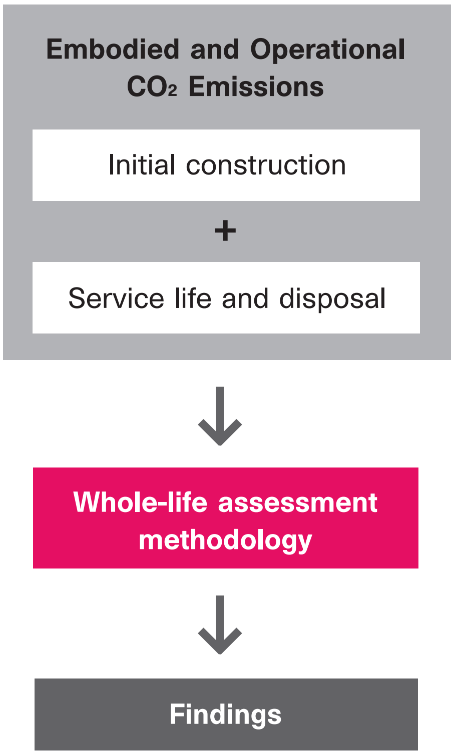


Figure 1 Components of whole-life assessment

Gathering Data for Whole Life Assessment

Basis of Assessment: Money or CO_2 Emissions?

Conventional whole-life assessment of building projects uses money-based measures of initial construction cost and costs-in-use: this is termed **life-cycle costing** or whole-life costing (WLC). Money-based measurement is familiar territory. Initial construction costs are routinely estimated with reasonable accuracy; costs-in-use can be more difficult to predict due to future uncertainty.

An alternative approach is to carry out whole-life assessment in terms of environmental impacts: this is termed **life-cycle analysis** (LCA). It is also a well-developed field, particularly for consumer products where the cradle-to-grave cycle is quite short, but it is increasingly applied to construction products and buildings.

At present, money-based WLC and environmental LCA are regarded as distinct methods of whole-life assessment. They diverge because money-based costs used for WLC do not take account of important factors like the damaging impact of CO_2 emissions. These are termed externalities and their exclusion from money-based costs is considered a market failure. Similarly, environmental impacts used for LCA are unaffected by some factors, like labour input, that contribute to the cost of construction. As a result, a design that performs well in money terms may perform badly in CO_2 emissions terms, and vice versa.

Project evaluation would be more effective if WLC and LCA could converge. Steps are being taken to include environmental externalities in market prices, though taxation, regulations and carbon trading. Eventually it may be possible to pursue the objective of low carbon design using money-based WLC, but until then the assessment of CO_2 emissions requires a separate LCA exercise.

Units of Assessment

The first efforts to quantify sustainability in buildings focused on energy consumption (measured in joules or kilowatt-hours). Later there was quantification in terms of carbon consumption (measured in kilograms or tonnes of carbon). Now the focus has shifted to emissions of greenhouse gases (GHG), because they are the critical agent for climate change.

Some older sources provide data in energy units, and these must be converted with CO_2 emissions factors; these factors are given in Figure 2A.

There are many types of greenhouse gas but the dominant one is CO_2. For convenience all GHG emissions are measured in terms of **CO_2-equivalent emissions** (kilograms or tonnes of CO_2 equivalent) (see Figure 2B). 'CO_2-equivalent emissions' is usually abbreviated to 'CO_2e emissions'.

You will sometimes see emissions expressed in terms of Carbon (C) although this is becoming less common. To convert carbon to CO_2 figures, simply multiply by 3.67– so 1 tonne of carbon is equivalent to 3.67 tonnes of CO_2.

Note that the term 'carbon emissions' is often used as shorthand for 'CO_2 emissions' and care should be taken to make sure the units used are consistent.

Figure 2A Emissions factors used to convert energy data into CO_2 emissions, or various fuels. Renewable energy has no GHG emissions. Source: Defra GHG Conversion Factors 2008

Fuel type	kgCO_2/kWh
Electricity (mains)	0.562
Electricity from CHP	0.304
Natural Gas	0.206
Fuel Oil	0.282
LPG	0.225
Coal	0.310–0.347
Wood Pellets	0.026

Figure 2A

Figure 2B The global warming potential relative of different greenhouse gases relative to CO_2. One tonne of methane is equivalent to 25 tonnes of CO_2. Source: Extract from PAS 2050:2008

Greenhouse gas	Global warming potential relative to CO_2
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298
HFC-134a	1430
HFC-143a	4470
Sulphur hexafluoride (SF_6)	22800

Figure 2B

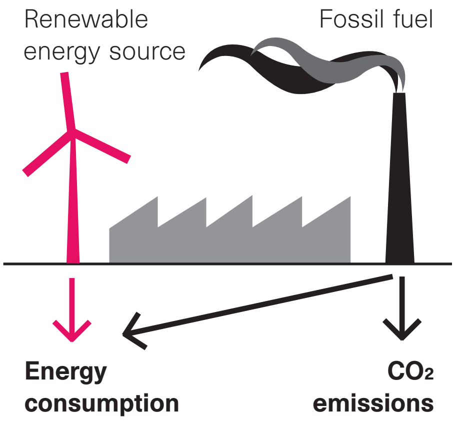


Figure 2C Energy-based analysis considers all energy consumed by a building regardless of source, whereas it is only the energy derived from fossil fuels that contributes to CO_2 emissions

Type of Assessment: Energy or Emissions?

Energy consumption and GHG emissions are often seen as interchangeable drivers in design. This may be true, for all intents and purposes, where all the fuel used to provide energy is fossil based – reducing the energy use of a building through improved design leads directly to a reduction in GHG emissions.

However, the issues are more complicated where there is low or zero carbon (LZC) energy, from low emissions fuels or renewable energy sources (Figure 2C). It is possible, for example, for an energy inefficient building to emit very little CO_2 if the energy used within it is renewable.

Design decisions that only focus on CO_2 emissions can lead to unexpected results. For example, when a building is supplied with electricity from a renewable source but uses gas-fired central heating, a focus on reducing CO_2 emissions would push the design towards minimising window area (to reduce heat loss) and increasing the use of electric lighting (as that comes from a renewable resource). However, it's clear that this would not make best use of daylighting.

Similarly, a material such as aluminium might not be responsible for significant CO_2 emissions even though its manufacture is energy-intensive, if that energy is from a renewable source such as hydro.

Energy and emissions both need to be factors in assessing low carbon design options.

Linking Money Based and CO_2 Emissions Based Data

When money-based and CO_2 emissions-based data for a given design are compared, some elements are likely to have relatively high CO_2 emissions and low cost, and others relatively low CO_2 emissions and high cost.

For example, elements with large quantities of CO_2-intensive but cheap materials, like cement, have high CO_2 emissions but low cost; whereas elements that are labour-intensive and use renewable materials, like thatching, have low CO_2 emissions but high cost. A worked example that compares money and emissions data is shown in Figure 3.

Money-based and CO_2 emissions-based data can be linked by introducing the **shadow price of carbon** (SPC). This is the current best estimate for the money value of the environmental impacts of CO_2 emissions that are not included in market prices – the environmental externalities. The SPC method is recommended in recent DEFRA guidance. www.defra.gov.uk/environment/climatechange/research/carboncost/index.htm

The SPC method works in the following way. Entries in the CO_2 emissions data-stream are multiplied by the SPC and added to the money-based entries, producing a CO_2-adjusted, money-based data-stream, which is then used for whole-life assessment.

DEFRA has set the SPC at £25/tCO_2e in 2007, rising at 2% per year. It is not actually a tax and the SPC is not part of the investor's cashflow: the objective is to weight a project's money-based data-stream, and therefore the outcome of whole-life assessment, in favour of low-CO_2 emissions designs.

Figure 3 Comparison of money-based and CO_2 emissions-based data for the initial construction of a distribution centre. Elements with high labour content (like external works) have disproportionately high money costs; elements with large quantities of CO_2-intensive materials (like substructure) push up the embodied CO_2 emissions

CO_2-saving efforts would focus on the substructure, but this would not be such a high priority for money-saving; whereas external works make a higher contribution in money terms than emissions terms. A design team could pursue savings in both aspects. Source: Davis Langdon, published in *Building* 2007, issue 41

	Money-based data		CO_2 emissions-based data	
Element	**£/m^2 gifa**	**%**	**kg CO_2e/m^2 gifa**	**%**
Substructure	59	17.4	147	42.3
Frame, upper floors and stairs	61	17.9	68	19.7
Roof	49	14.3	42	12
External walls, windows and doors	15	4.3	13	3.8
Internal walls and doors	1	0.2	2	0.7
Internal finishes	4	1.3	6	1.6
Building services installation	32	9.4	30	8.7
External works and services	81	24	9	11.1
Preliminaries		38		11.1
Totals	339	100	347	100

Exclusions: site preparation, site abnormals, fit-out and operating equipment, professional fees

Figure 3

Embodied and Operational CO_2 Emissions

A building is responsible for CO_2 emissions in two ways – embodied and operational emissions.

Operational emissions occur when fuel from fossil sources (gas, oil, coal or peat) is burnt, emitting CO_2 to the atmosphere. When electricity that has been generated with fossil fuels is consumed at the building, the CO_2 emissions actually occur at the generating station, but they are counted as part of the building's emissions, on the principle that the end-user is responsible for 'upstream' emissions.

Exactly the same principle of 'upstream' emissions is the basis on which the building's embodied CO_2 emissions are measured. Every construction material or component in the building has been through processes that involved CO_2 emissions, and when the materials or components are used, their past emissions are said to be 'embodied' in the building.

The whole-life CO_2 emissions of a building are the sum of its operational and embodied CO_2 emissions (see Figure 4).

The whole-life is broken down into three phases – construction, service life and disposal.

- In the construction phase all emissions are regarded as embodied
- In the service life there are operational emissions plus some embodied emissions from component replacement and refurbishment
- In the disposal phase there are emissions from demolition and disposal operations.

The scale of the CO_2 emissions of different kinds varies from case to case. For example, disposal is more significant for short-life components than for structural elements with long service lives, and operational emissions are minimal in 'zero carbon' buildings.

When materials are recovered for recycling or re-use in other buildings, their embodied CO_2 emissions could be deducted from the project from which they are recovered. However, the

Figure 4 The build-up of CO_2 emissions in the whole-life of a building or component. Time runs from top to bottom of the diagram.

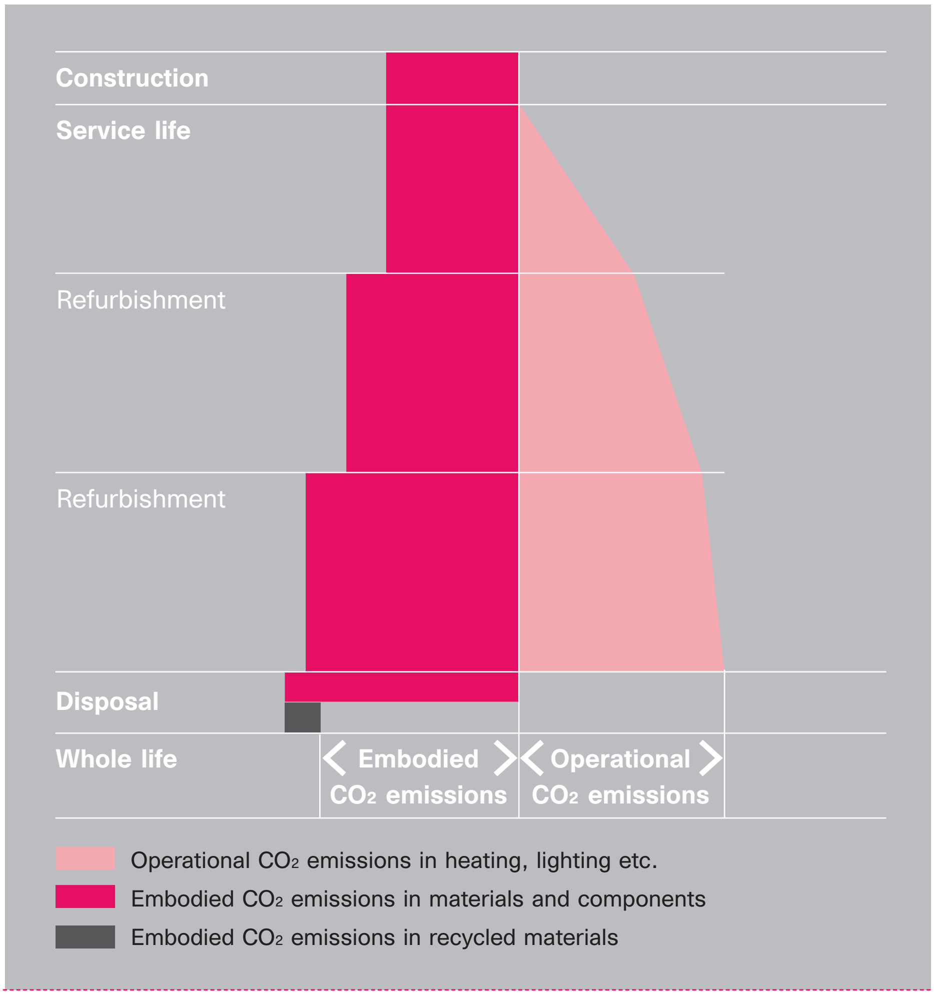


Figure 4

emissions are not eradicated: they are transferred to the new uses, becoming part of their embodied CO_2 emissions.

It used to be assumed that operational CO_2 emissions during a building's service life dominated its embodied emissions. This meant that there was little need to justify design features that added to embodied emissions if they reduced operational emissions.

However, with more efficient design standards the balance is changing and embodied emissions form an increasing share of total CO_2 emissions. This means that more care must be taken to check whether design features that add to embodied emissions are actually justified by reductions in operational emissions – that is, to check against the risk of over-investment.

Figure 5 identifies some valuable sources of data about the embodied CO_2 of different materials and components..

CO_2 Emissions: Construction Phase

CO_2 emissions embodied in the construction phase of a project are usually divided into two parts – first, 'cradle to factory gate' emissions, and second, emissions of site operations, including the transport of materials and components to site.

'Cradle to factory gate' data for the embodied CO_2 emissions of standard materials and components can be obtained from several sources (see Figure 5). Generally, materials with high emissions consume a lot of fossil fuel in their manufacture, for example, the firing of kilns for brick or cement production (see Figure 6).

There is considerable variation in the data, because many factors have a bearing on embodied CO_2 emissions:

- **Energy sources** Energy consumption in manufacturing and transport accounts for much of the embodied emissions in building materials and components, but the

Figure 6 Typical 'cradle to factory gate' embodied CO_2 emissions values for building materials by mass. Source: Inventory of Carbon and Energy, University of Bath

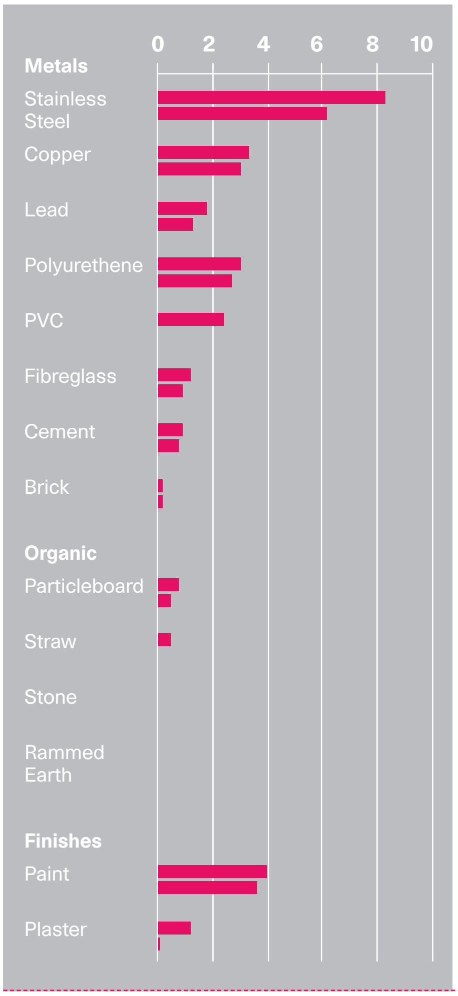


Figure 6

Embodied CO_2 data		
Buildcarbonneutral	On-line embodied carbon estimator from USA with landscape emphasis	www.buildcarbonneutral.org
Inventory of Carbon and Energy	Downloadable database of building materials	www.bath.ac.uk/mech-eng/sert/embodied
BMCI (Building Materials Carbon Indicator)	Downloadable self-assessment software	www.eccm.uk.com/httpdocs/calculators/Building_Materials_Carbon_Indicator_v4_3.xls
ENVEST	Subscription service from BRE	envestv2.bre.co.uk
Benchmark data		
CarbonBuzz – RIBA/CIBSE platform	Non-subscription membership scheme to establish benchmark data for operational energy use in buildings	www.bre.co.uk/carbonbuzz
Component service life data		
HAPM Component Life Manual	Housing Association Property Mutual	
The BPG Building Fabric Component Life Manual	Building Performance Group	
Life Expectancies for Building Components: surveyors' experiences of buildings in use	BCIS	
Construction Durability Database	Subscription service from Building Life Plans	www.componentlife.com
Component Durability Database	Subscription service from Building Performance Group	www.bpg-uk.com/index.html

Figure 5 Sources of CO_2 – emissions data

emissions vary with the source of energy (see page 4, Figure 2A).

- **Renewable energy** The use of renewable energy generates no CO_2 emissions. For example, the processing of aluminium from raw materials is energy-intensive, but many aluminium plants use renewable hydro-electric power so the embodied CO_2 emissions are greatly reduced.
- **Manufacturing efficiency** Embodied CO_2 emissions figures should reduce over time as manufacturing processes and transport become more CO_2-efficient in response to carbon taxes and other pressures.
- **Recycling** The manufacturing or processing of re-used materials can give emissions savings; for example, using recycled aluminium typically requires only one-eighth of the energy of new aluminium, and generates one-fifth of the emissions (the figure for aluminium in Fig.5 assumes one-third recycled content).
- **Boundaries** When estimating embodied CO_2 emissions, the system boundaries are critical. For example, emissions generated by the consumption activities of the workforce involved in manufacturing and construction (including their travel to work) are excluded from the embodied emissions of components. In effect, labour content is assumed to make zero contribution to embodied emissions, whereas it is a major factor in money-based assessment.
- **Sequestering** Some timber or plant-based materials in buildings are said to sequester CO_2, because CO_2 was taken from the atmosphere during their growth; this CO_2 would be released if the material decayed, but the release is temporarily halted while it remains in use as a building material.
- **Quantities** The embodied CO_2 emissions per unit of a material must be related to the quantities used in a building – if a high-emissions material is used in a small quantity, it may make only a small contribution to overall embodied emissions and offer limited scope for CO_2 emissions savings (and vice versa).
- **Feedstock** Some building products, such as plastics, use fossil carbon as a raw material. This 'feedstock' use contributes to resource depletion, but CO_2 emissions are much lower than when fossil carbon is burnt as fuel (see the Green Guide weighting of 'Fossil fuel depletion' in Figure 10, p10).

Because of differences in manufacturing and transport, there are variations in the 'cradle to factory gate' CO_2 emissions of the same material from different sources. At present suppliers are rarely able to provide embodied CO_2 emissions data for materials they stock, but data of this type will undoubtedly become more widely available in the future.

The embodied CO_2 of site operations, including transport to site, must be added to the 'cradle to factory gate' figures. This contribution to embodied emissions varies widely between projects but rarely exceeds 20% of the 'cradle to factory gate' emissions.

The largest input of embodied emissions occurs in the initial construction. However, during the service life, the additional embodied emissions from component replacement can be considerable. An example of the whole-life build-up of embodied CO_2 emissions is shown in Figure 4 (see page 6).

Figure 7 Embodied CO_2 emissions in a ground floor slab. It is important to transform unit values into installed values; for example, a high-CO_2 emissions material that is used in very small quantities makes a small contribution to installed emissions.

Quantification identifies the elements that should be the focus of CO_2-saving efforts; here, the three elements – excavation, disposal of excavated material and concrete – that account for 94% of the embodied emissions of the slab. Source: Davis Langdon, *Building* 2007, issue 41.

Element	$kgCO_2e$ / unit	$kgCO_2e$ / m^2 floor area
Excavation / PFA mix	11.1 (m_3)	6.7
Disposal of excavation	16.7 (m_3)	10.0
Blinding, 75mm thick	9 (m_3)	0.7
Concrete, 200mm thick	309.1 (m_3)	61.8
Reinforcement, A252 mesh	0.44 (kg)	1.7
Movement joints	8.7 (m)	0.4
Damp proof membrane	0.7 (m_2)	0.7

Slab area 103.2m^2. Concrete mix based on 30% PFA substitution of OPC.
Exclusions: demolition and disposal of slab at end of life.

Figure 7

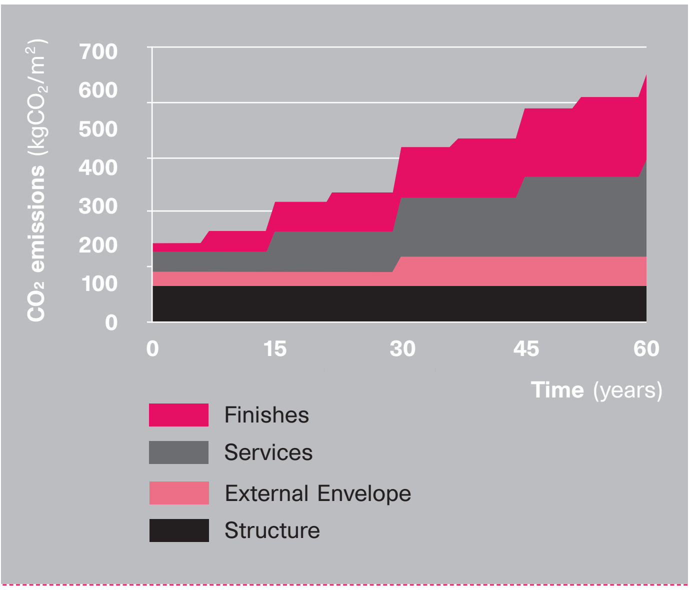


Figure 8

Figure 8 Diagram showing the build-up of embodied emissions for a typical residential building, as components are periodically replaced. The whole-life embodied emissions profile is very different from that of the initial construction.

Source: *Total Energy Use in Refurbishment: Avoiding the Over Commitment of Resources* by H Mulligan & K Steemers, 2002

Despite uncertainties, the broad distinctions between high- and low-embodied emissions design can be established from available data. An identical design built in different ways in different places will have varying embodied CO_2 emissions, due to factors such as the sourcing of materials and construction methods that are usually seen as outside the designer's control but over which the designer can have significant influence. You should base your decision-making on the best available data about embodied emissions and not give up because of data uncertainties.

There are many unresolved questions relating to embodied emissions. The Government's consultation on zero carbon homes – published in December 2008 – says, '...this consultation does not set out to address the issue of 'embodied energy' expended in the construction of the home, the manufacture and transportation of the materials used and the demolition and recycling of materials. The EU is currently exploring new harmonised standards in this area and as a result the Government is not seeking to develop national standards in this area while that work is under way'.

CO_2 Emissions: Service Life and Disposal

Whole-life assessment needs year-by-year estimates for CO_2 emissions. These could be developed for the full service life of the buildings or the whole-life assessment study period if this is shorter. You should also include emissions estimates for disposal if this is in the scope of your assessment. These building emissions include:

- Fossil fuel for heating, hot water, lighting, cooling, lifts, etc (operational emissions)
- Regular maintenance (mixture of embodied and operational emissions)
- Component replacement and refurbishment (mostly embodied emissions)
- Disposal (embodied emissions).

Some studies also include the CO_2 emissions of activities and processes taking place in the building; this wider definition largely applies to the UK Government's Display Energy Certificate (DEC) scheme for non-domestic buildings. Designers usually focus their attention on the emissions listed above.

Forecasts of a building's service life CO_2 emissions face many uncertainties (see Figure 9).

Using some simplifying assumptions and projecting current data into the future, you can bring together a forecast of service life CO_2 emissions. However, it is likely that the actual CO_2 emissions will diverge significantly and unpredictably from this forecast – increasingly so, the further the data is projected into the future.

Arguably, some uncertainty in service life forecasts may not matter for whole-life assessment if standard assumptions are used to compare design alternatives. However, some changes could upset the ranking of design alternatives; for example, if the emissions from electricity declined in the future due to on-site renewable generation, the evaluation of alternatives with high electricity consumption would improve relative to others with lower electricity consumption.

Source of uncertainty	Simplifying assumption
Operational CO_2 emissions for a building depend on the pattern of use, which is unpredictable (and usually exceed design predictions).	Assume a 'typical' pattern of use (see *Low Carbon Standards and Assessment Methods* within this suite of Climate Change Tools).
CO_2 emissions from electricity consumption may vary with future methods of generation, which cannot be predicted.	Assume that today's emissions per kWh remain the same, or predict a scenario of future change.
The service lives of materials and components, and the replacement intervals, are variable; and replacements are not always made on a like-for-like basis.	Assume standard service lives and like-for-like replacement.
What about technical change, change in regulations, fashion, etc?	Ignore these contingencies.

Figure 9 Uncertainties facing forecasts of a building's service life CO_2 emissions

The emissions impacts of disposal are regarded as being part of parts of a building's embodied emissions. As noted above, when materials or components are recovered for recycling or re-use in other buildings, their embodied CO_2 emissions could be deducted from the project from which they are recovered. However, the emissions are not eradicated: they are transferred to the new uses, becoming part of their embodied CO_2 emissions. Although estimates of recovered emissions are highly uncertain, recycling and re-use are sustainable practices that should be adopted when feasible.

Many of the difficulties in assembling service life data are simply due to the very long life of buildings, compared to, say, food packaging where the entire life-cycle from raw materials to disposal or recycling takes place in days or weeks. Whole-life data for buildings will always be more uncertain than for short-life products.

Given the uncertainty in long-term CO_2 emissions estimates, it may not be worthwhile to assemble very precise and detailed data for a long time period. Most buildings' service life CO_2 emissions are dominated by a few major items, and it may be more sensible to assemble estimates for these items only. Similarly, uncertainty increases with time so it may be reasonable to assemble data for a shorter study period than the building's expected life, say a 20 or 30 year study period as is commonly used in whole-life costing.

Green Guide to Specification

An important source of data about the environmental impact of construction is the *Green Guide to Specification*. It was first published in 1996. The 4th revised edition was published in 2008, and the information is now available on-line.

The *Green Guide* is concerned with the overall environmental impact of construction. It takes account of both the initial construction and periodic like-for-like replacement of components over 60 years and also disposal/recycling. Replacements are assumed to take place at standard intervals, and operational data is used for estimating their impact.

Data is given for 'functional units', such as walls, windows, etc. For each functional unit, alternative specifications are described and rated on a six-point A+ to E scale against 13 aspects of environmental impact; a summary rating is also given, based on a weighted average of the 13 aspects (see Figure 10). **At present no quantified data on CO_2 emissions is given in the *Green Guide*, but its scope is being extended.**

In effect, the *Green Guide* consists of many micro-whole-life assessment exercises. It can help you to identify low environmental impact specifications, but it does not provide source data for a CO_2 emissions-based whole-life assessment of design alternatives.

Figure 10 The Green Guide assesses the environmental impact of construction components against 13 factors, with percentage weightings attached to each factor in the summary assessment. Note the low weight now attached to fossil fuel depletion. Source: *Methodology for Environmental Profiles of Construction Products*, BRE, 2007 (Table 3).

Impact	Percentage weight
Climate change	21.6
Water extraction	11.7
Mineral resource extraction	9.8
Stratospheric ozone depletion	9.1
Human toxicity	8.6
Ecotoxicity to freshwater	8.6
Nuclear waste (higher level)	8.2
Ecotoxicity to land	8.0
Waste disposal	7.7
Fossil fuel depletion	3.3
Eutrophication	3.0
Photochemical ozone creation	0.2
Acidification	0.05

Figure 10

How to Analyse for Whole Life Assessment

Trade-offs between Initial Emissions and Service Life Emissions

Whole-life assessment is normally used to compare alternative designs or specifications. If one alternative has lower initial CO_2 emissions and lower service life CO_2 emissions than the others, it can be selected without the need for further analysis; and an alternative with higher initial CO_2 emissions and higher service life CO_2 emissions can similarly be rejected.

The situation is more interesting when comparing alternatives with low construction CO_2 emissions and high service life CO_2 emissions, against others with high construction CO_2 emissions and low service life CO_2 emissions. It is then necessary to analyse the trade-off between construction and service life CO_2 emissions using a whole-life assessment methodology.

Rudimentary Approach: The 'Simple Payback' Method

Whole-life assessment is often used to compare a 'base' case with enhanced specification alternatives that have higher construction CO_2 emissions and lower service life CO_2 emissions.

The task is to establish whether the benefits from the enhanced specification alternatives are sufficient to justify the extra investment and, if there are several alternatives, which of them performs best from a whole-life perspective.

A simple but rudimentary method is to divide the extra construction CO_2 emissions by the annual savings in service life CO_2 emissions. This gives a 'payback period' in years: short 'payback periods' are preferred.

Alternatives with a 'payback period' that is longer than the component's service life should normally be avoided.

One problem with this method is that it doesn't look beyond the end of the 'payback period'. An alternative with a five year 'payback' and a six year service life would be rated ahead of a component with a six year 'payback' and a 20 year service life.

The 'simple payback' method is useful as a preliminary guide, but it ignores important factors and can be misleading.

Superior Approach: The Principle of Whole Life Assessment

A better approach to whole-life assessment looks beyond the 'payback period', taking account of CO_2 emissions over the whole-life of the project or a study period of, say, 20 to 30 years. All values in the data stream are aggregated, to give whole-life emissions. When comparing alternatives, the one with the lowest whole-life emissions is preferred.

The simplest way of aggregating initial and service life CO_2 emissions is to add them all together, giving a cumulative value that rises year by year. This can be plotted on a graph, (see Figure 11) with a line for each alternative being compared. Each line starts at Year 0 (the year when construction is completed) at a value equal to the embodied CO_2 emissions of construction, and then rises year by year during the service life. The steepness of the line corresponds to the annual CO_2 emissions (mainly operational emissions). The lines often have vertical steps, when components are replaced (mainly embodied emissions).

The interesting thing is whether the lines on the cumulative emissions graph (Figure 10) cross. When this happens, it means that a design alternative that had higher construction emissions ends up with lower whole-life emissions. The alternative with the higher initial CO_2 emissions is preferred.

The graph also indicates how long it takes before the lines cross – equivalent to the 'payback period'. The more distant the crossover point, the less convincing is the case for the alternative with higher construction CO_2 emissions, due to increasing uncertainty in estimates of future emissions.

The lines on the cumulative graph that start low and end up high represent under-investment; and lines that start off high and stay high represent over-investment. The line that ends up with the lowest whole-life 'emissions cost' represents efficient investment.

The same exercise can be carried out using money-based costs, as in whole-life costing. Cumulative graphs for CO_2 emissions, money costs, and CO_2-adjusted money costs are compared in Figure 12 for four house types: a 'base' design corresponding to mainstream practice, and three low- CO_2 alternatives, the 'low', 'medium' and 'ambitious' types. The graphs shows the contrast between money-based and CO_2 emissions-based assessment.

Figure 11 Cumulative graph for three alternatives. Typical form of a whole-life assessment of three alternatives, represented on a cumulative graph. The starting points of the lines correspond to the initial investment in the alternatives – the embodied CO_2 emissions in construction. The gradients indicate the rate of CO_2 emissions during the service life, with vertical 'steps' indicating component replacement or refurbishment. If two lines cross, the higher initial investment is more than outweighed by lower emissions during the service life; if they don't cross, the alternative with the lower investment cost also performs better over the study period. In this example, alternative A represents under-investment; C is over-investment; and B is efficient

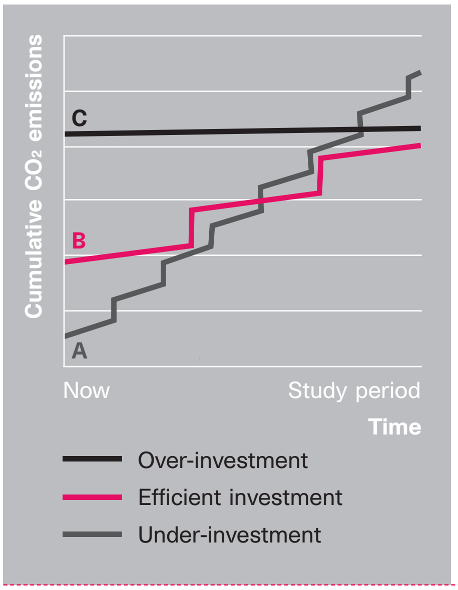


Figure 11

Figure 12A Cumulative CO_2 emissions for four house types. After about 13 years the base is worst; the 'low' spec is best over 25 years, but the 'ambitious' spec just beats it over 50 years. Other than the 'base' alternative, whole-life performance is substantially determined by initial embodied CO_2 emissions

Note: No allowance for renewable generation, and no embodied energy from component replacement

Figure 12B Cumulative money cost for four house types. The 'base' type begins with the lowest cost, but the 'low' spec performs best over 25 and 50 years. Other than the 'base' alternative, whole-life performance is substantially determined by initial construction cost

Figure 12C Cumulative costs with the addition of the shadow price of carbon (SPC). The impact of the SPC increases later in the life-cycle. The 'low' spec still performs best over 25 and 50 years. Note that the 'base' spec is out-performed by the 'ambitious' spec over 50 years

Source for Figure 12: S Potter 'Low Energy Housing Design' DipArch dissertation, University of Cambridge, 1999

Figure 12A Cumulative CO_2 emissions for four house types

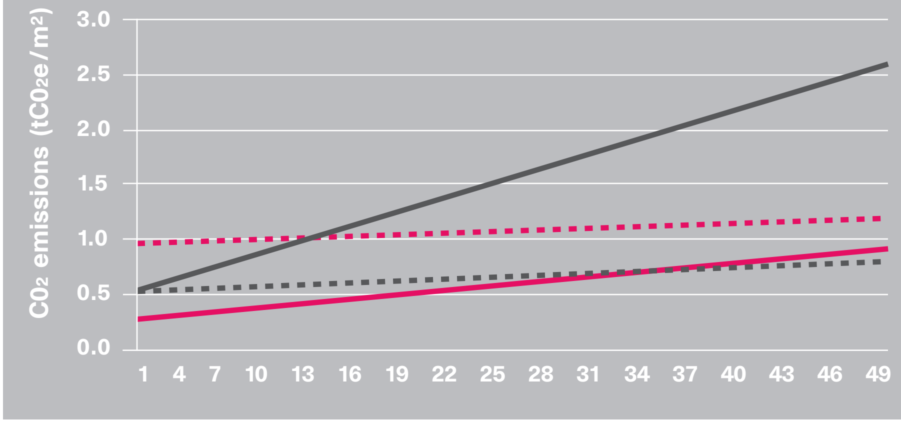


Figure 12B Cumulative money cost for four house types (no discounting)

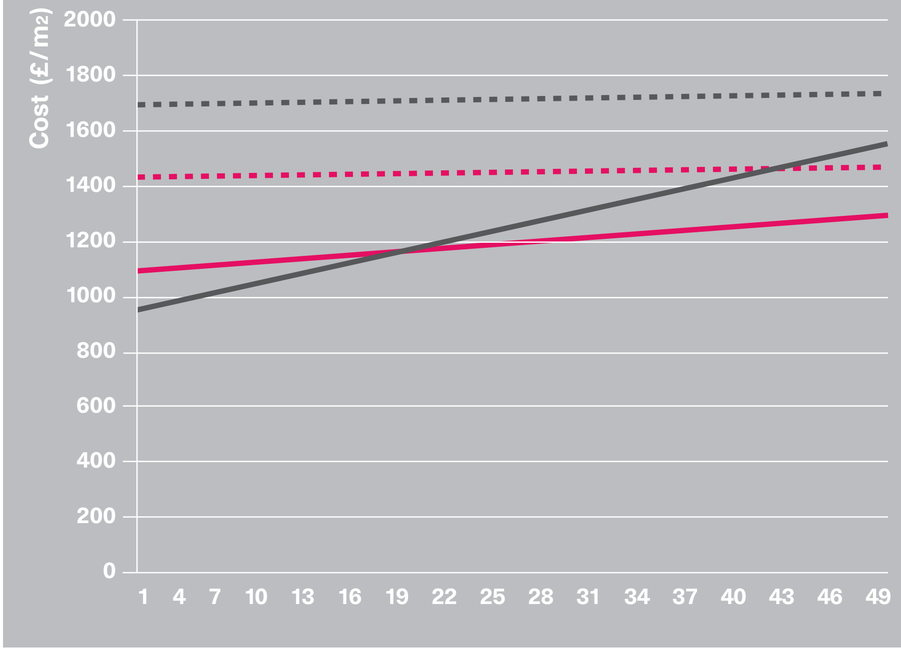
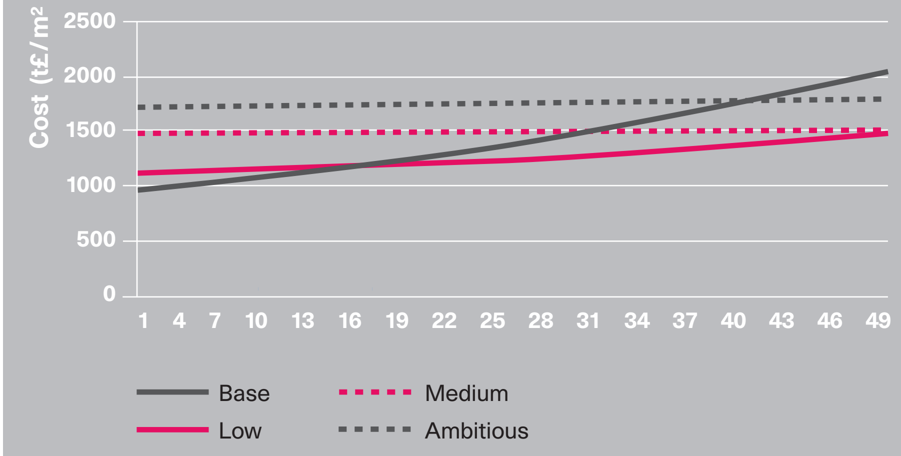


Figure 12C Carbon-adjusted money-based cumulative costs (no discounting)



Dealing with Time: Time Preference and Uncertainty

Whole-life assessment in which all entries in the data-stream are simply added together assumes that CO_2 emissions count for exactly the same in today's decision-making whether they arise now or at any time in the study period. This is questionable for three reasons:

- **Time preference** (i.e., we may care less about the future than the present) – Everyday experience and numerous experiments have shown that people have time preference, attaching more weight to events that occur now or in the near future compared to distant events; this increases progressively as events become more distant. Society as a whole may have a lower time preference than individuals, on the basis of inter-generational sustainability and fairness.
- **Changing wealth** or optimism (future costs and benefits will have a different impact depending on whether we are better off or worse off compared to today). In economics there is usually an optimistic assumption of rising material wealth over time, and therefore it is assumed that a given cost or benefit will be less important in the future when we are wealthier than it is now. With climate change, there is an expectation of declining conditions, so this assumption is problematic.
- **Risk or uncertainty** (i.e., we can't be sure that the forecast events will actually occur). As described earlier, all estimates of CO_2 emissions are subject to uncertainty, especially service life estimates where uncertainty increases with time. One response is to reduce the weight attached to uncertain future emissions compared to certain emissions occurring now or in the immediate future.

In money-based whole-life costing, these three factors lead to the convention of **discounting**, whereby future estimated costs or benefits are scaled down by a fixed percentage rate for every year between now and the time of occurrence. A high percentage rate (or **discount rate**) corresponds to a short-term perspective that greatly reduces the weight attached to what happens in the future; a low or zero discount rate gives more weight to future estimates and implies a longer-term perspective.

When discounting is applied to a cashflow, the result is called the **net present value** (NPV) of the cashflow. The methodology is called discounted cashflow (DCF).

HM Treasury sets a discount rate of 3.5% per year for money-based appraisal of public sector investment; it is made up in the following way:

- Time preference: 1.5% per year
- Rising wealth: 2% per year
- Risk: this is ignored

In contrast, private sector investors can have money-based discount rates as high as 20% per year.

The Treasury's discount rate has no risk component, or 'risk premium', perhaps because the Government assumes that the risks in different projects will more or less balance out. Non-Government investors are less likely to ignore risk. The consequence of ignoring risk is that safe but unspectacular projects appear less attractive than exciting projects that have a higher risk of under-performing: ignoring risk can lead to over-investment.The variation of risk between projects means that it is difficult to set a 'standard' discount rate.

The discount rate has a dramatic effect on the outcome of whole-life costing. Figure 13 shows the money-based cumulative graphs for the four house types for discount rates of 3.5% and 10%.

With discounting, especially with higher discount rates, distant costs and benefits have almost no impact in whole-life value. In pragmatic terms, this means that there is little point in collecting data for very long study periods when there is discounting.

Discounting is a well-established practice in money-based whole-life costing, but there is less experience of discounting for CO_2 emissions. There is unresolved debate about the economics, psychology and ethics of discounting in relation to climate change and this has massive implications for public policy.

Figure 13A Present values (NPV) of money cashflows for four house types, with 3.5% discount rate. The 'base' and 'low' spec are just about equal for a 25 year cashflow; for a 50 year cashflow the 'low' spec is just better. Note that the crossing point of the 'base' and 'low' spec lines is pushed further into the future compared to the undiscounted case (Figure 12B)

Figure 13B Present values (NPV) of money cashflows for four house types, with 10% discount rate. The 'base' and 'low' spec lines no longer cross, so the 'base' performs best for 25 and 50 year cashflows. Service life costs after about 25 years make virtually no impact on present

Figure 13A Cumulative money-based present value for four house types (3.5% discount rate)

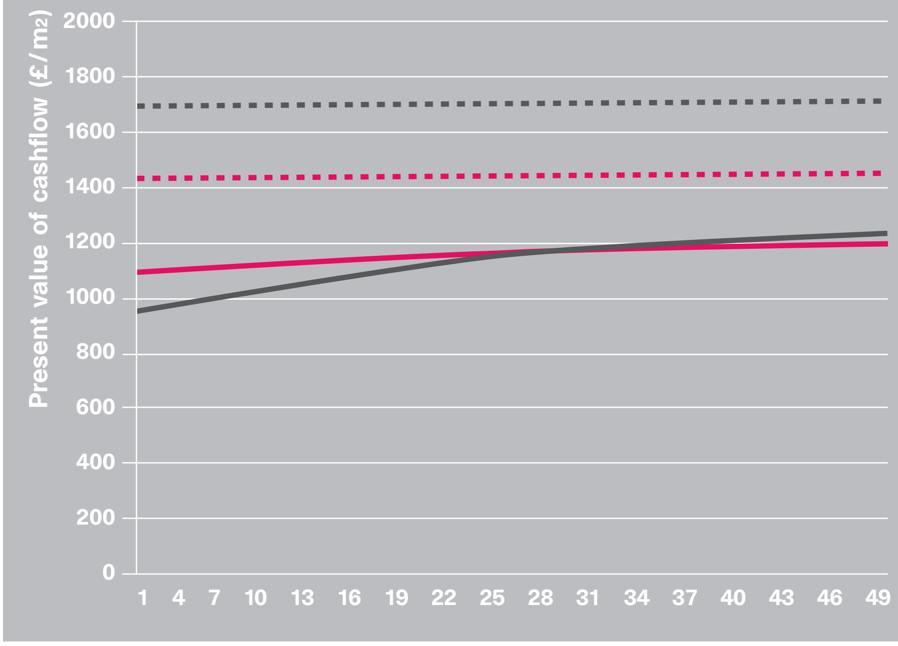
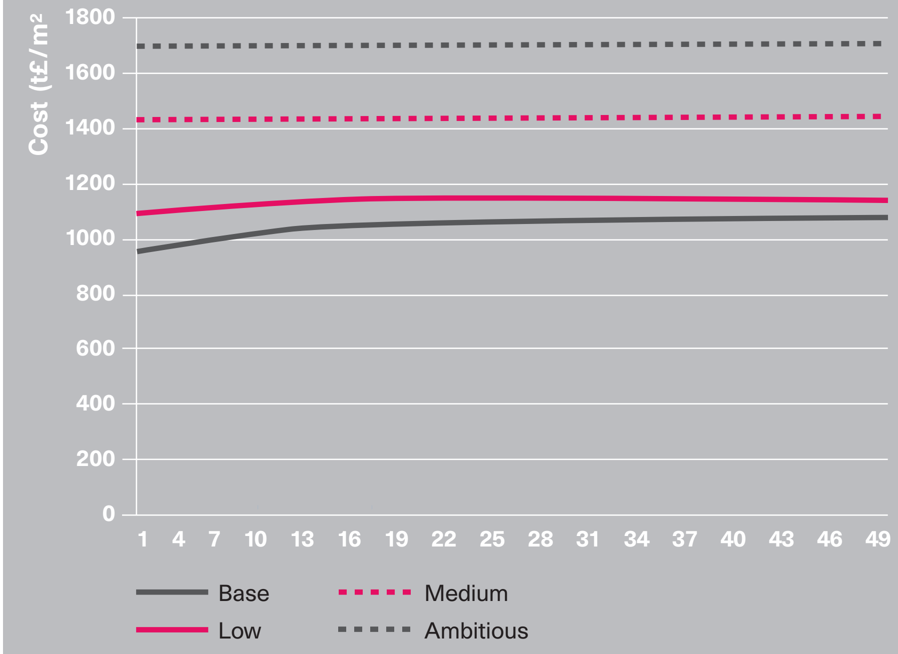


Figure 13B Cumulative money-based present value for four house types (10% discount rate)



The current draft standard for assessing lifecycle GHG emissions applies a weighting system for delayed emissions that scales down their impact (PAS 2050:2008, Annex B – **shop.bsigroup.com/**en/Browse-by-Sector/Energy--Utilities/PAS-2050

The questions of whether to discount, and if so at what rate, are not primarily design issues, but if a discount rate is used in whole-life assessment, you should make every effort to ensure that careful consideration has been given to setting an appropriate rate. The use of an unsuitable discount rate will distort the results of whole-life assessment and could lead to worthless or counter-productive investment.

Even when quantified discounting is not used, the three factors described above – time preference, optimism and risk – will contribute to an investor's judgement when making trade-offs between initial, short-term emissions and long-term, service life emissions.

Getting the Maximum Benefit: Opportunity Costs

When evaluating a low-CO_2 design proposal, it is not enough to check whether savings in service life emissions exceed any extra emissions in construction (i.e. the 'payback period' is less than the whole-life study period). A further and essential test is whether greater benefits could be obtained by investing the same resources in a different way – can you get 'more bang for your buck'?

This involves checking whether there are any 'opportunity costs' attached to the proposal – what might be thought of as 'lost opportunity' costs.

Suppose there are two designs with identical embodied CO_2 in construction, but one has lower service life CO_2 emissions. If it is decided that the less efficient design should be built, the extra service life emissions are called an opportunity cost attached to that decision. It represents the value of an opportunity that has been missed.

The reduction or elimination of opportunity costs is an essential part of sustainable decision-making.

Opportunity cost minimisation is equivalent to the 'least cost first' principle in selecting CO_2 reduction strategies, recommended by DEFRA. If, say, insulation was the most effective way of reducing CO_2 emissions in the housing stock, and boiler replacement came next in effectiveness, then a budget for sustainable refurbishment should be spent on insulation until there were no more uninsulated homes, and then investment should switch to boiler replacement. Investing in boiler replacement when there were still uninsulated homes would reduce benefits in relation to investment and therefore incur an opportunity cost.

Avoiding opportunity costs usually means looking at a bigger picture. For example, one might think that there is no need for energy efficiency in building A that uses renewable energy; but if the renewable energy saved by upgrading building A could have been delivered to fossil-fuel burning building B, then the potential CO_2 emissions reductions in building B would be an opportunity cost of the inefficient, renewables-wasting building A.

Well-intentioned regulations can sometimes incur opportunity costs. For example, on-site generation of renewable energy is desirable, but it is sometimes inefficient and takes resources that could give greater benefits if used in other ways. The shortfall in benefits would be an opportunity cost of the regulation.

An example of opportunity costs for the house types described above is given in Figure 14.

Figure 14 Opportunity cost
Suppose that 10 houses are to be built, using the types described above (Figures 12 and 13). There is a grant of £90K for additional construction costs compared to building 10 'base' houses, to be spent on reducing CO_2 emission

The £90K grant could be used to replace one 'base' house by an 'ambitious' spec CO_2-saving house (say, with labour-intensive rammed earth walls and thatched roof) – Strategy A. The costs and CO_2 emissions are shown in Strategy A

However, the same £90K grant for carbon-saving could be used to replace five 'base' houses by five 'low' spec houses – Strategy B. The costs and CO_2 emissions are shown in Strategy B

The CO_2 emissions from Strategy B are much lower than from Strategy A. If Strategy A is pursued instead of Strategy B, an opportunity cost of 768 tCO_2e is incurred

Strategy A	Construction cost per house (120m^2)	CO_2 emissions per house over 50 years	Cost for project	CO_2 emissions for project
'Base' spec (9 houses)	£114K	305 tCO_2e	£1.026m	2745 tCO_2e
'Ambitious' spec (1 house)	£204K	98 tCO_2e	£204K	98 tCO_2e
Total			**£1.23m**	**2843 tCO_2e**

Strategy B	Construction cost per house	CO_2 emissions per house over 50 years	Cost for project	CO_2 emissions for project
'Base' spec (5 houses)	£114K	305 tCO_2e	570K	1525 tCO_2e
'Low' spec (5 houses)	£132K	110 tCO_2e	£660K	550 tCO_2e
Total			**£1.23m**	**2075 tCO_2e**

Figure 14

The opportunity cost principle applies equally to the work of design teams: it is wasteful to expend a great deal of design effort on ideas that lead to small savings in CO_2 emissions, if the same design effort applied to other ideas could achieve greater savings.

Design for Uncertainty: 'Lifecycle Options'

Whole-life assessment is fairly straightforward if you have good data about CO_2 emissions; but assembling the data, especially service life data, is difficult. It is always subject to uncertainty, increasingly so for more distant estimates.

One response is to take a short-term view, focusing only on short-term CO_2 emissions and giving little weight to more distant estimates. It tends to defeat the object of whole-life assessment, which aims to take a long-term view.

A different approach to uncertainty is to seek robust design strategies that perform well across a range of future scenarios. Because the future is unpredictable, there is a risk that decisions based on today's predictions will turn out to be poor decisions. Rather than make risky decisions today, it would be preferable to make decisions in the future when better data is available. For example, rather than predicting what will be the best fuel to use in 20 years' time and designing a building that has to use that fuel, with the risk of bad outcome if the prediction turns out to be wrong, it would be better to design a multi-fuel system so that the choice of fuel can be made in the future.

Opportunities for future decisions can be called **lifecycle options**. All designs incorporate some lifecycle options, such as the ability to change finishes, etc. Other lifecycle options can be deliberately acquired at the time of design, often with an additional investment. For example, lifecycle options such as increasing a ceiling height to allow for changes in use or making special provision for a future switch to renewable energy, could add to a project's construction emissions. Investing in lifecycle options may be a good investment because the events that will take place in a building's service life are usually uncertain, and decisions based on predictions that turn out to be wrong could be very wasteful.

You should consider the following when thinking about robust design strategies with lifecycle options:

- The value of lifecycle options increases with uncertainty (if we could make accurate predictions there would no need for lifecycle options). Lifecycle options are most valuable in situations of high uncertainty, e.g., involving new technologies
- Only acquire lifecycle options when the value generated exceeds the investment required for their acquisition
- In designing for low CO_2 emissions, priority should be given to building-in features that cannot be upgraded later, such as ground floor slab insulation, in preference to features that can be upgraded later, like roof-mounted renewables generation, where there is a lifecycle option for future upgrading
- Lifecycle options are part of project value and should be considered in whole-life assessment – their omission may distort the outcome; for example, a multi-fuel boiler may require greater investment, so it will appear to reduce whole-life value unless the lifecycle option value is taken into account.

Qualitative Analysis: The Self-Assessment Matrix

Quantified whole-life assessment is challenging and is often carried out by specialists. There is therefore value in a simpler, qualitative method that all members of a project team can use. The self-assessment matrix below is a simple, non-quantified tool that can help you to get started on the investigation of whole-life assessment. Ideally, it should increase motivation for investigating the issues more deeply, by going on to use more rigorous, quantified methods.

Figure 15 shows a self-assessment matrix method that scores a project or a decision against five variables; the resulting profile is compared with a set of templates that indicate an appropriate strategy for achieving whole-life value. This method aims to minimise the risk of under- or over-investment, and provide outline guidance on efficient design strategies.

To use the matrix, the design team scores the alternatives under consideration with respect to five types of uncertainty (note that for 'Restriction of capital', 'low' means that the investor can afford to invest for long-term benefits; and that for 'Curtailment of pay back period', 'low' means that the investor does take a long-term view.)

When all rows have been scored, the resulting pattern can be compared to typical templates. The guidance attached to the relevant template indicates the appropriate strategy for whole-life value.

Sources of uncertainty	low	-ve	+ve	high
Restriction of capital				
Uncertainty of technology				
Uncertainty or regulation				
Uncertainty of use				
Curtailment of payback period				

Figure 15

Figure 16 Self-assessment matrix – typical templates

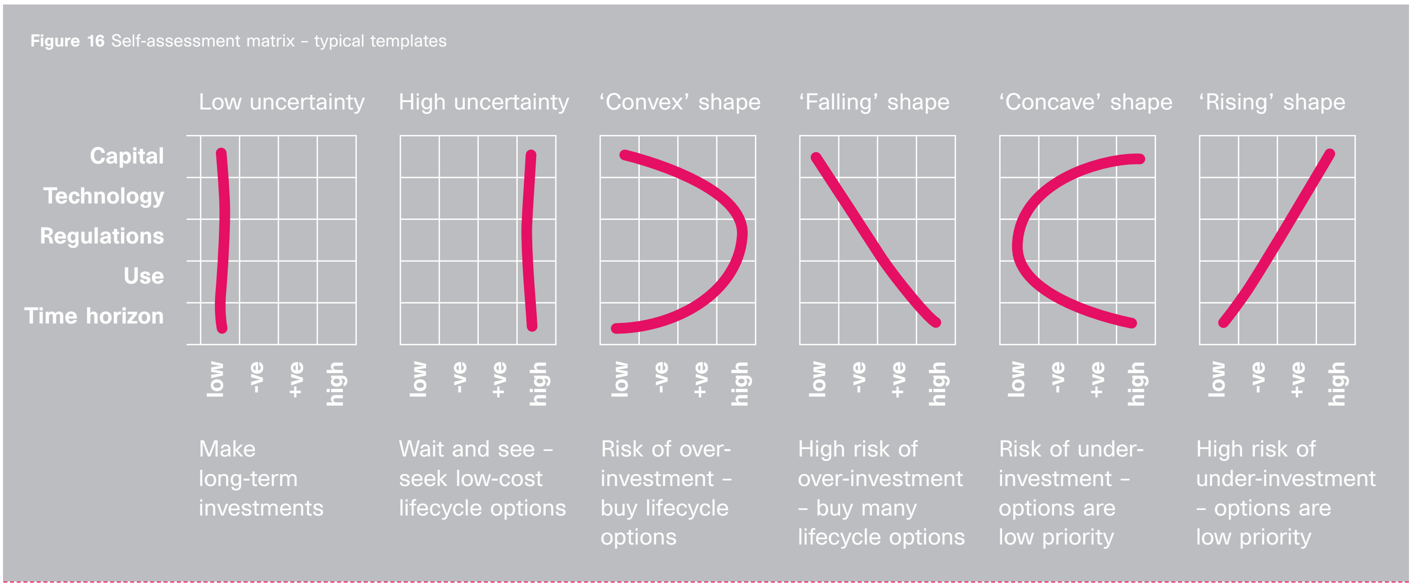


Figure 16

Conclusion

Whole-life assessment is conceptually simple but can be difficult to apply, mainly because of data problems. With further development, data sources will no doubt get better, and new ideas like the shadow price of carbon and lifecycle options will make whole-life assessment more useful.

Meanwhile, you should press for a whole-life perspective in all design decision-making, using common sense, experience, and whole-life assessment as appropriate.

The following key points may be useful:

1. Quantification of the embodied and current CO_2 emissions associated with a design helps to indicate where to focus efforts to reduce CO_2 emissions.

2. Select design alternatives that generate large, certain or early reductions in CO_2 emissions, over those that generate weaker, uncertain or distant benefits.

3. Don't rely on detailed predictions or fine distinctions: whole-life assessment is imprecise so only big differences are credible.

4. Aim for robust design strategies that work well for a diversity of future scenarios, especially in situations of high uncertainty.

5. For elements where there are no opportunities for future upgrading, prioritise initial investment in building to a high specification to minimise CO_2 emissions.

6. For elements where there are opportunities for future upgrading, consider deferring initial investment and upgrading to higher specifications later.

7. Before investing resources in a CO_2 emissions-saving strategy, stand back and check that there isn't a completely different way of investing the resources to generate greater CO_2 emissions savings.

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www.bcis.co.uk

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www.clientsuccess.org.uk

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www.bsi-global.com
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