The contribution to UK climate mitigation targets from reducing embodied carbon in the construction sector

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Publication of chapters and contributions

The candidate confirms that the work submitted is his own, except where work which has formed part of jointly-authored publications has been included. Whilst some elements of chapters have been directly reproduced, much of the content has been modified and additional sections included to allow a more comprehensive analysis of the topic. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate also confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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In this paper the candidate's contribution was to: design the research; conduct the literature review; work alongside Anne Owen in making adjustments to the UK MRIO model; evaluate the model results; provide interpretation and discussion; and produce the core text and graphics. John Barrett and Peter Taylor supervised the work and contributed to the writing.

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In this paper the candidate's contribution was to: design and implement the model; undertake the scenario analysis; analyse results; and produce the core text and graphics. John Barrett and Peter Taylor supervised the work and contributed to the writing.

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Furthermore, contributions as an author were made in the following conference paper.

Wiedmann, T., Crawford, R., Seo, S. and Giesekam, J. (2013) The Industrial Ecology Virtual Laboratory and its application to sustainability and environmental engineering - the case of low carbon living. *Sustainable Engineering Society (SEng) 2013 Conference,* 18-20 September 2013, National Convention Centre, ACT, Australia.

Acknowledgements

We face a problem that could be addressed with relatively minor shared sacrifices, but instead there is a mass effort to ignore, defer, deny, and lie. Knowing that it will fall mostly on our own children, and their kids. On the part of people – of a generation – who are farther from hardship than almost any in history. Global warming doesn't bother me as much as what it is revealing about humans.

Professor Steven Sherwood (a notable climate scientist)

In the face of such widespread apathy and wilful ignorance, it would be easy to lose faith in the idea that humanity can come together and solve the shared problem of climate change. Yet for every denier and delayer I have met these past few years I have encountered an equally inspiring individual slowly leading us forwards. These acknowledgements are for all those people who have replenished my faith that this wicked problem can be solved.

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There's naethin that restores yer faith mare in human nature than meetin sum poor bastard thas jus as mad as yersel

Rab C. Nesbitt

Abstract

The UK construction industry faces the daunting task of expanding output whilst achieving substantial greenhouse gas emission reductions. Recent building life cycle assessments show that embodied carbon constitutes a growing proportion of whole life emissions. However, the precise distribution of embodied carbon along sector supply chains; the range of mitigation options available to practitioners and the potential policy responses have received little attention. This thesis addresses a number of these outstanding issues.

The thesis commences with an analysis of the distribution of emissions along construction sector supply chains using Multi-Region Input Output modelling. The results of this analysis are combined with a large database of building carbon assessments to form a hybrid UK Buildings and Infrastructure Embodied Carbon model. This novel combination of bottom up project data and top down sector data provides a much needed link between sector carbon mitigation targets and project carbon intensity targets. A scenario analysis using the model suggests that, if external factors progress within the range of Government projections, current practices will be insufficient to meet sector targets. Therefore additional embodied carbon mitigation strategies must be implemented.

One such mitigation strategy is increasing the use of alternative building materials with lower embodied carbon. This thesis presents a comprehensive overview of the barriers to uptake, based upon a literature review, survey of construction professionals and interviews with industry leaders. This research highlights the current lack of drivers for embodied carbon assessment and mitigation. In response, the thesis presents possible policy responses and industry-led actions as a series of dynamic adaptive policy pathways developed through a participatory approach with key stakeholders.

Collectively this thesis depicts the sizeable contribution embodied carbon abatement could make to the achievement of long-term UK climate mitigation targets and the interim response required from industry practitioners, institutions and policy makers.

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Nomenclature

Where necessary, the abbreviations below are defined within the text. For ease of reading, the terms carbon and emissions are used throughout as shorthand for the basket of greenhouse gas emissions monitored by DECC. Where specific figures are quoted these are expressed in terms of carbon dioxide equivalent (CO_2e).

ASBP – Alliance for Sustainable Building Products
BCIS – Building Cost Information Service
BCO – British Council for Offices
BIM – Building Information Modelling
BIS – Department for Business, Innovation and Skills
BRE – Building Research Establishment
BREEAM – Building Research Establishment Environmental Assessment Method
BSI – British Standards Institute
CASBEE – Comprehensive Assessment System for Built Environment Efficiency
CCC – Committee on Climate Change
CCS – carbon capture and storage
CIC – Construction Industry Council
CLC – Construction Leadership Council
CLT – cross-laminated timber
CRC – Carbon Reduction Commitment
CRC – completely recyclable concrete
CSR – corporate social responsibility
DAPP – dynamic adaptive policy pathways
DCLG – Department for Communities and Local Government
DECC – Department of Energy and Climate Change
DEFRA – Department for Environment, Food and Rural Affairs
DER – Dwelling Emission Rate
DfD – design for deconstruction
EC – European Commission
ECO – Energy Companies Obligation
EPBD – Energy Performance of Buildings Directive
EPD – Environmental Product Declaration
ETFE – Ethylene Tetrafluoroethylene
EU ETS – European Union Emissions Trading Scheme
FEES – Fabric Energy Efficiency Standard
FiTs – Feed-in Tariffs
FRP – fibre reinforced polymers
GBC – Green Building Council
GCB – Green Construction Board

GHG – greenhouse gas
HQM – Home Quality Mark
ICE – Institute of Civil Engineers
ICR – Infrastructure Carbon Review
IEA – International Energy Agency
IGT – Innovation and Growth Team
IO – input-output
IPCC – Intergovernmental Panel on Climate Change
KPI – key performance indicators
LCA – life cycle assessment
LCC – life cycle costing
LCI – life cycle inventory
LEED – Leadership in Energy and Environmental Design
MEPS – Minimum Energy Performance Standards
MFA – Material Flow Analysis
MMC – modern methods of construction
MPA – Mineral Products Association
MRIO – multi-region input-output
NDBSD – Non-domestic Building Stock Database
NIP – National Infrastructure Pipeline
OBR – Office for Budget Responsibility
OPC – Ordinary Portland Cement
PAS – Publically Available Specification
PXC – path exchange method
REAP – Resource Efficiency Action Plan
RHI – Renewable Heat Incentive
RIBA – Royal Institute of British Architects
RICS – Royal Institute of Chartered Surveyors
SAP – Standard Assessment Procedure
SCM – supplementary cementitious material
SIC – Standard Industrial Classification
SIPS – structural insulated panels
SPA – structural path analysis
TER – Target Emission Rate
VOA – Valuation Office Agency
UKCG – United Kingdom Contractors Group
UKERC – United Kingdom Energy Research Centre
UKGBC – United Kingdom Green Building Council
UN – United Nations
WBCSD – World Business Council for Sustainable Development

WCB – waste create bricks

WGBC – World Green Building Council

WRAP – Waste and Resources Action Programme

1. Introduction

> *There's one issue that will define the contours of this century more dramatically than any other, and that is the urgent and growing threat of a changing climate*

U.S. President Barack Obama, UN Climate Change Summit, 2014

1.1 Background

The actions of humanity have fundamentally altered ecosystems throughout the world for over 8000 years (Hughes et al., 2013). However, the past century has seen an unprecedented increase in human impacts (McNeill, 2001). Over the 20th century the world increased its annual fossil fuel use by a factor of 12, whilst extracting 34 times more material resources (EC, 2011). Humans have significantly altered three quarters of the world's terrestrial habitats and continue to extract 60 billion tonnes of raw materials each year (Ellis, 2011; Krausmann et al., 2009). Meanwhile emissions from our activities have driven atmospheric concentrations of carbon dioxide, methane and nitrous oxide to levels that are unprecedented in at least the last 800,000 years (IPCC, 2014). It has been suggested that humanity is now transgressing three planetary boundaries for rate of biodiversity loss, changes to the global nitrogen cycle, and climate change (Rockström et al., 2009). The evidence of a changing climate is "*unequivocal*" (IPCC, 2014) and the anticipated increases in the frequency of extreme weather events, threats to water and food security and the massive loss of biodiversity represent a fundamental risk to the health and livelihoods of a large portion of the global population.

The Intergovernmental Panel on Climate Change (IPCC) has advised that "*substantial emissions reductions over the next few decades can reduce climate risks in the 21st century and beyond, increase prospects for effective adaptation, reduce the costs and challenges of mitigation in the longer term and contribute to climate-resilient pathways for sustainable development*" (IPCC, 2014). This message has fuelled a growing response from the international community, including commitments to The Kyoto Protocol, The Copenhagen Accord, and the landmark Paris Agreement adopted in December 2015. This agreement commits 196 countries to developing "*aggregate emission pathways consistent with holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*" (UN, 2015). These global agreements have been supplemented by the adoption of a vast array of national targets, frameworks and climate policies. Since 1997, the number of climate change laws and policies has doubled every 5 years, and, as of June 2015, 75 countries and the EU have framework laws or policies to address mitigation (Nachmany et al., 2015). National economy-wide emission reduction targets now cover over 75% of global emissions. The UK for its part introduced legislation in 2008 requiring that "*the net UK carbon account for the year 2050 is at least 80% lower than the 1990 baseline*" (Climate Change Act 2008).

Mitigation measures within the built environment are critical to the achievement of these climate targets, with recent studies suggesting buildings offer the greatest abatement opportunities for reducing greenhouse gas (GHG) emissions in the short term (IPCC, 2014; McKinsey & Company, 2009). Buildings are the largest single sector for energy use worldwide and are responsible for an estimated third of global carbon emissions (Weisz & Steinberger, 2010; Allwood et al., 2010). Aside from the energy consumed in operation, the construction of buildings and the manufacture of building products are responsible for substantial raw material consumption, waste generation and associated carbon emissions. Indeed, it has been estimated that over 70% of all materials ever extracted are situated in the built environment (Berardi, 2013).

In the UK, the volume of carbon dioxide emissions that the construction sector influences is significant, accounting for an estimated 47% of the national total (BIS, 2010). The majority of these emissions are associated with the operation of structures but the share attributable to their construction, maintenance and disposal is growing (Ibn-Mohammed et al., 2013). The Government's principal strategy for the sector, Construction 2025, challenges the industry to halve carbon emissions from the built environment in the next ten years whilst meeting growing demand for buildings and infrastructure (HM Government, 2013). This ambition is supported by regulation requiring improvements in building performance and reductions in operational energy use. However, a recent industry routemap identified that reductions in operational emissions alone would be insufficient to meet sector targets (GCB, 2013b). Substantial reductions in the so-called *embodied carbon* associated with the initial production, maintenance and disposal of buildings will also be required. However, despite the need for action, embodied carbon assessment and mitigation remains the preserve of a minority of industry practitioners (UKGBC, 2014a). Whilst over recent years the industry has expanded guidance and raised the profile of embodied carbon, the response remains piecemeal. Few clients are requesting embodied carbon assessment and policy makers have yet to introduce meaningful requirements or incentives. In the absence of substantive drivers and coordinated industry action, the contribution of embodied carbon mitigation to ambitious sector and national emission reduction targets remains unclear.

This thesis explores the contribution that reductions in embodied carbon emissions from construction could make to UK climate mitigation targets through a mix of quantitative and qualitative research methods. Respective chapters address the origin of emissions from multiple perspectives; provide an overview of embodied carbon reduction strategies; explore barriers to adoption of low carbon alternatives; model future embodied emission scenarios; and propose a range of policy responses.

The following sections of this introductory chapter set the scene. Section 1.2 provides an overview of UK climate mitigation targets. Section 1.3 introduces the main challenges facing the UK construction industry. Section 1.4 charts the genesis of current industry strategy and climate mitigation targets. Section 1.5 summarises the research rationale. Section 1.6 states the research aims and objectives. Section 1.7 briefly describes the core methodologies employed. Finally, Section 1.8 introduces the structure of the remaining chapters.

1.2 UK climate mitigation targets

Successive prime ministers have described climate change as "*one of the most serious threats that this country faces*" (Cameron, 2014) if not "*the greatest challenge that we face as a world*" (Brown, 2009). As part of global efforts to reduce GHG emissions, the UK has adopted a set of challenging targets both independently and as part of a combined international effort.

The first of these targets was adopted in 1997, whereby, as a signatory to the Kyoto Protocol, the UK committed to reduce emissions of certain GHGs by 12.5% from 1990 levels by 2008-2012 - a mark it comfortably achieved. The UK's target was 681 $MtCO_2e$; estimates of 2012 Kyoto basket emissions totalled 582.2 $MtCO_2e$ (DECC, 2015a).

In 2007 EU leaders made a combined commitment that Europe would cut its emissions by 20% from 1990 levels by 2020. As part of this, the UK is obligated to cut its emissions by 16% on 2005 levels (EC, 2009). This is to be followed by a 40% cut by 2030, with long-term reductions of 80-95% by 2050 (EC, 2015b). The EU has also adopted complementary interim targets for renewable energy and energy efficiency to support this goal.

The UK's self-imposed targets go further still, with the ground-breaking Climate Change Act, introduced in 2008, aiming for a 34% reduction in GHG emissions from 1990 levels by 2020 and an 80% reduction by 2050 (Climate Change Act, 2008). This is facilitated by a carbon budgeting system, whereby cumulative emissions are limited over 5 year periods. These Carbon Budgets are recommended by the Committee on Climate Change (CCC) and, at the time of writing, are as noted in Table 1. The first four budgets, covering the period up to 2027, have been set into law. Government proposals for the fifth carbon budget are not anticipated until later in 2016 (CCC, 2015a). The carbon budgets are expressed both in absolute terms and as reductions against a 1990 baseline, when annual UK territorial emissions were 809.4 $MtCO_2e$.

The term *territorial emissions* refers to an accounting system that includes only GHG emitted within national borders. This is in contrast to a *consumption-based emissions* accounting system that allocates emissions according to location of final consumption, irrespective of the actual location of emission. For a more detailed description of the distinction between these emissions accounting systems see Barrett et al. (2013). As a large emitter by either measure, the construction sector is expected to play a key role in meeting UK emission reduction targets (HM Government, 2011).

1.3 An introduction to the UK construction sector

The construction sector has always been of major importance to the UK economy, representing 8.3% of the UK's gross value added and directly employing 6% of the UK's workforce (HM Government, 2010; ONS, 2013c). These figures nearly double when the full supply chains supporting the industry are considered (UKCG, 2012). For example, around 20% of UK manufacturing is construction products (Speedman et al., 2011).

The sector has undergone fundamental changes over recent decades, in large part driven by the rise of the 'sustainable' and 'green building' agendas. 'Green building' now represents a trillion dollar global industry, of which the UK is a world leader (WGBC, 2013). Meanwhile domestic demand motivated by demographic trends and the need for low carbon infrastructure, such as renewable energy installations, represents a sizeable package of future work for the industry (HM Treasury, 2014). As remarked by Paul Morrell, the Government's former Chief Construction Adviser, "*over the next 40 years the transition to low carbon can almost be read as a business plan for construction*" (HM Government, 2010).

With the Government's central estimates suggesting that the national population will grow to 78.4 million by 2050 (an increase of 14 million people from 2015 (ONS, 2011)), the construction industry faces a profound challenge in meeting anticipated demand. The UK's existing housing stock is already inadequate in both quality and number, with nearly 8 million 'non-decent' homes requiring urgent refurbishment and over 1.7 million people on the social housing waiting list at the time of writing (National Refurbishment Centre, 2010; DCLG, 2014). The growing

Table 1: UK Carbon Budgets

	Period	Budget Level ($MtCO_2e$)	% reduction below 1990
1st carbon budget	2008-12	3,018	23%
2nd carbon budget	2013-17	2,782	29%
3rd carbon budget	2018-22	2,544	35%
4th carbon budget	2023-27	1,950	50%

housing shortfall is expected to exceed 2 million homes by 2020 if current trends continue (Lyons, 2014). In the longer term, DCLG project that an additional 3.6 million households will require new homes by 2030 (DCLG, 2015b). Meanwhile Government retrofit targets necessitate improvements to the fabric of 13,000 homes per week - one home every minute - until 2050 (National Refurbishment Centre, 2010). Over the same period the industry must undertake the replacement of the majority of the UK's electricity generating plant with low carbon alternatives and fulfil government plans to invest in many pieces of large-scale infrastructure, such as high speed rail and highway networks. The package of works set out in the National Infrastructure Pipeline already constitutes £466bn of investment and is set for further expansion (HM Treasury, 2014). Meeting the demand motivated by these demographic trends will undoubtedly incur significant environmental impacts.

In a typical year, the sector is already responsible for over 90% of non-energy mineral extraction, requiring over 420 million tonnes of material resources and energy equivalent to just under 8 million tonnes of oil (Smith et al., 2003; Constructing Excellence, 2008). Furthermore, every year the sector uses 6500 ha of land; is responsible for a third of all industry-related pollution incidents; and generates in the order of 100 million tonnes of waste (Wang et al., 2014; DEFRA, 2011). The construction industry also influences the bulk of UK carbon emissions both indirectly, through facilitating sustainable practices amongst end users of buildings and infrastructure, and directly through its choice of building materials and operational practices (HM Treasury, 2013). At an aggregate level, it has been estimated that the production and transport of building materials, combined with the construction, operation and maintenance of UK structures, results in equivalent carbon dioxide emissions of some 202 $MtCO_2e$ per year (Steele et al., 2015). Consequently successful delivery of UK climate mitigation targets depends heavily upon the development of a low carbon construction industry. The transition to such an industry requires significant investment in new skills, technologies and construction products, motivated by a clearly defined long-term strategy.

1.4 The evolution of strategy for a low carbon construction industry

The Government's strategy for a low carbon construction industry has evolved from a multitude of high profile reviews, consultations and routemap exercises over a period of decades. This section provides a brief summary of these reviews and describes the evolution of current strategy.

1.4.1 Construction 2025

The essence of current strategy is distilled in Construction 2025, which envisages a ten year transformation to a sustainable industry that capitalises on anticipated global growth in green and sustainable building and "*leads the world in low-carbon and green construction exports*" (HM Government, 2013). This implies a greater focus upon low carbon design expertise and manufacture of low carbon building products, in an effort to distinguish British firms from international competitors in an increasingly competitive global marketplace. The strategy contains four headline targets:

» A 50% reduction in greenhouse gas emissions in the built environment;
» A 33% reduction in the initial cost of construction and the whole life cost of built assets;
» A 50% reduction in the overall time, from inception to completion, for new build and refurbished assets;
» A 50% reduction in the trade gap between total exports and total imports for construction products and materials.

These targets are intended to motivate an industry that "*drives and sustains growth*" and leads the world on smart construction, research and innovation. This vision for a more sustainable industry is to be "*underpinned by strong, integrated supply chains and productive long term relationships*", with an increasingly diverse and up-skilled workforce. Amongst the many commitments made in support of this vision, the strategy launch coincided with the inception of the Construction Leadership Council (CLC), initially a 30-strong group of government and industry representatives. The CLC have since met three times a year to discuss priority issues in delivering the strategy. In July 2015 the Government announced that the Council would be reduced to 12 members, and that the supplementary post of Chief Construction Adviser would be discontinued. Both of these changes have been viewed by industry practitioners as a "*disaster*" that threatens to undermine support and delivery of the Construction 2025 targets (Pringle, 2015). Many have particularly criticised the omission of architects, front line designers and any representatives of the material supply chain from the revamped CLC (Sinfield, 2015).

1.4.2 Prior reviews and recurring criticism

Whilst Construction 2025 sets out a broad set of priorities and ambitious targets, it suffers somewhat from defining a vision of the future industry, not so much by what it will be, but by what it will not be. Instead of presenting a clear image of the characteristics of a future industry, it depicts alternatives to the commonly cited faults of the current industry. This is perhaps best summarised by the excerpt: "*Construction in 2025 is no longer characterised, as it once was, by late delivery, cost overruns, commercial friction, late payment, accidents, unfavourable workplaces, a workforce unrepresentative of society or as an industry slow to embrace change*" (HM Government, 2013 p. 18). All these criticisms of the industry are long standing, and have been the subject of numerous high profile reviews dating back to the 1990s, including those by Latham and Egan (Latham, 1994; Egan, 1998). Indeed, a failure to deal with these recurring criticisms has hampered the development of a sustainable construction industry since sustainability was first highlighted as a key cross-cutting sector issue in the early 2000s in both Egan's follow up report Accelerating Change (Strategic Forum for Construction, 2002) and David Pearce's report on the role of construction in relation to sustainable development (Pearce, 2003). These four reviews largely set the agenda for the modernisation and development of a more sustainable industry throughout the early 2000s and were supported by the publication of an increasing array of white papers and policy statements.

A number of the most high profile policies and incentives, such as the now defunct Code for Sustainable Homes and Zero Carbon Homes, were announced in the run up to the adoption of the Climate Change Act in 2008. In an attempt to draw together this growing raft of policy measures, the Government published their Strategy for Sustainable Construction (HM Government, 2008). This document constituted the first coherent strategy for a low carbon construction industry, summarising already announced targets and setting out the Government's future policy direction. The focus was on delivering value for money, safe construction sites, and fit for purpose buildings within the context of new environmental targets. The strategy included a number of actions and deliverables including voluntary targets for a 50% reduction of construction, demolition and excavation waste to landfill compared to 2008 by 2012; and a 15% reduction in carbon emissions from on-site construction processes and associated transport in the same period. Both of these targets were subsequently missed, with on-site emissions increasing in real terms (Construction Manager, 2014). Many of the strategy's other deliverables, particularly related to training, ultimately became casualties of the subsequent recession. In the same year, Egan was also asked to assess the industry's progress over the past decade at implementing his recommendations. After bemoaning the persistent lack of effective collaboration in construction practice, he told a House of Commons reception: "*I'd probably only give the industry about 4 out of 10, and that's basically for trying*" (Egan, 2008).

1.4.3 Reviews following the financial crisis

In 2009, the Wolstenholme report 'Never Waste a Good Crisis' provided a further review of progress in implementing the Egan agenda in the context of more challenging economic circumstances and additional environmental pressures (Constructing Excellence, 2009). The report showed through a survey of nearly one thousand industry professionals and a review of progress against the Construction Industry Key Performance Indicators (introduced in response to the Egan report) that there had been "*too little change*", and that Egan's principles had been "*too narrowly adopted and at too slow a rate*". Performance on the hundreds of demonstration projects monitored by Constructing Excellence in the intervening period demonstrated that the Egan targets were achievable, with demonstration projects out-performing typical industry projects by 19% across the KPIs. However, there was little evidence of lessons from demonstration projects being learnt by the wider industry. The report authors were left with the impression of "*a few shining examples of progress against a backdrop of fairly entrenched behaviour*." Indeed, survey respondents suggested change had only reached a "*minority club*" and that "*there is no evidence that the progress made in a small percentage of the industry's activity will ever spread to the rest.*" In the meantime, a failure to adopt the Egan principles had resulted in all KPI targets being missed, with the exception of profitability. The report authors concluded that: "*It is clear that the stated aim of genuinely embedding the spirit of changes has not been met. There is not enough evidence of a united resolve across the diverse constituencies of UK construction to achieve Egan's vision of a modern construction industry. Where there are commitments, they tend to be superficial and expedient, not tangible and sustainable*" (Constructing Excellence, 2009 p. 10). However, the report authors argued that the surrounding economic crisis presented an ideal opportunity to transform industry practice.

Shortly before Christmas 2009 the Government commissioned a further strategic review, focussing specifically on the fitness of the construction industry in delivering the low carbon agenda. This review was undertaken by a new Innovation and Growth Team (IGT) featuring over 100 people from industry and Government, and chaired by newly appointed Chief Construction Adviser Paul Morrell. The IGT's extensive findings were published in 2010 (HM Government, 2010). The 230 page report constituted the most comprehensive document on the topic to date, and contained 65 recommendations covering a variety of aspects of the industry. Two of these specifically mentioned embodied carbon:

"Recommendation 2.1: That as soon as a sufficiently rigorous assessment system is in place, the Treasury should introduce into the Green Book a requirement to conduct a whole-life (embodied + operational) carbon appraisal and that this is factored into feasibility studies on the basis of a realistic price for carbon.

Recommendation 2.2: That the industry should agree with Government a standard method of measuring embodied carbon for use as a design tool and (as Recommendation 2.1 above) for the purposes of scheme appraisal."

The majority of the report's findings were accepted, with the Government recognising the industry's need for clarity, incentives and cooperation. The response was published in the form of the joint Government and industry Low Carbon Construction Action Plan the following year (HM Government, 2011).

The Action Plan laid out 155 actions for Government and industry across 8 key themes. These covered a wide range of topics including: establishing a suitable sector routemap and interim targets; significant public sector procurement reform; revisions of various pieces of legislation; greater training and a focus on 'greening the construction curriculum'; developing strategies to address perceived skills shortages; launch of additional online resources (such as Carbon Action 2050); commissioning of additional targeted research; support for development of embodied carbon measurement tools; and developing a programme for widespread implementation of Building Information Modelling (BIM) - which will be required on all publically funded projects by 2016. The Green Construction Board (GCB) was established in 2011 to monitor progress and provide leadership on implementation of the Action Plan. At the time of the last progress update, 57% of the actions agreed in the Government response had been completed (GCB, 2013a). This represents substantial but far from prolific progress.

1.4.4 Establishing a sector routemap

As part of this ongoing work, the GCB undertook a project to develop a Low Carbon Routemap for the Built Environment (GCB, 2013b). The Routemap indicated the range and scale of actions required to achieve an 80% reduction in GHG emissions attributable to the built environment by 2050. The development of the Routemap culminated in publication of an interactive tool, a wall chart and a detailed report which sets out the calculation method and three detailed scenarios (*business as usual*; *central* and *80% carbon reduction*). Under the *80% Carbon Reduction Scenario* the authors projected a reduction in total emissions to 42 $MtCO_2e$ by 2050. This required capital carbon reductions of 39% by 2050 relative to a 2010 baseline alongside reductions in operational emissions of 85% for domestic properties and 77% for non-domestic properties. This resulted in an overall shift to 60% operational and 40% embodied emissions by 2050. The Routemap authors concluded that meeting the target is "*challenging but technically possible*" and "*would require maximum uptake of technically viable solutions in all sectors, including implementation of technologies that at present do not have a financial return on investment over their lifetime*" (GCB, 2013b p. 2). The study also concluded that embodied carbon "*must start to be addressed in tandem with operational carbon*" to meet sector targets. The report was well received and broadly praised for making a strong first attempt at establishing a viable forward plan with limited data and resources. However, the drastic scale of action required in the 80% reduction scenario came as a shock to many in the industry. Launching the Routemap Paul Morrell stated that "*my personal view is that the assumptions the model makes are so heroic that I don't believe anyone will believe it will happen in the timeframe*." Beyond the headlines, there are also a number of reasons to criticise the Routemap's treatment of embodied carbon, further discussed in Section 3.3. These concerns suggest that there is good reason to believe the situation is even more desperate than suggested by the already "*challenging*" 80% reduction scenario.

A further outcome from the Low Carbon Construction Action Plan was the production of the ICE's Low Carbon Infrastructure Trajectory report on the means of providing infrastructure networks with greatly reduced carbon emissions (ICE, 2011). In the report the Infrastructure Trajectory group outlined some key steps and possible contributing elements to the evolution of infrastructure out to 2050. The report established five priorities (ICE, 2011 pp. 5–6):

» Establish a shared understanding of the purpose and performance requirements of UK infrastructure.
» Establish an effective, transparent and predictable carbon price as the centre piece of a package of incentives for developing low carbon infrastructure.
» Systematically apply the concepts of Capital Carbon and Operational Carbon to infrastructure decision making.
» Establish a high level evaluation methodology for use at the appraisal stage of infrastructure projects.
» Make greater use of demand management.

In response to these priorities, the ICE committed to establishing banks of case studies; updating codes and standards; embedding carbon evaluation in professional training; and leading research in establishing evaluation methodologies and means of improving carbon efficiency. The report's authors strongly advocated the use of capital carbon and operational carbon benchmarks at the project appraisal stage. The term capital carbon is the preferred terminology for embodied carbon in the infrastructure segment of the industry because it accords with the concept of capital cost. Though the terms are often used interchangeably there are subtle differences in the definitions as highlighted by Anderson (2014). It is envisioned that, once developed, such benchmarks will be a critical driver of future reductions in infrastructure emissions. The authors also strongly emphasised the need for demand management measures, as population growth is expected to exacerbate peak demand for infrastructure services. They suggest that this increased demand cannot be met through increased building alone. Overall, the measures seek to overturn the "*prevalent industry practice*" that "*tends to seek carbon savings at later stages in projects when the most radical options to reduce carbon are no longer possible*" (ICE, 2011 p. 6). This should be supplanted by an emphasis on reductions through option appraisal and demand management.

1.4.5 The Infrastructure Carbon Review and PAS 2080

The ICE report was followed by the Infrastructure Carbon Review (ICR) (HM Treasury, 2013). The ICR was jointly developed with government by the GCB's Infrastructure Working Group, and the resulting report was endorsed by 20 large organisations upon its publication. The review set out a series of actions for government, clients and suppliers to reduce carbon from the construction and operation of the UK's infrastructure assets. The core priorities lay in developing:

- strong leadership to drive cultural engagement with the low carbon agenda;
- innovation to identify and implement new thinking by defining outcomes and allowing creative responses;
- procurement that incentivises the whole value chain to collaborate and outperform targets.

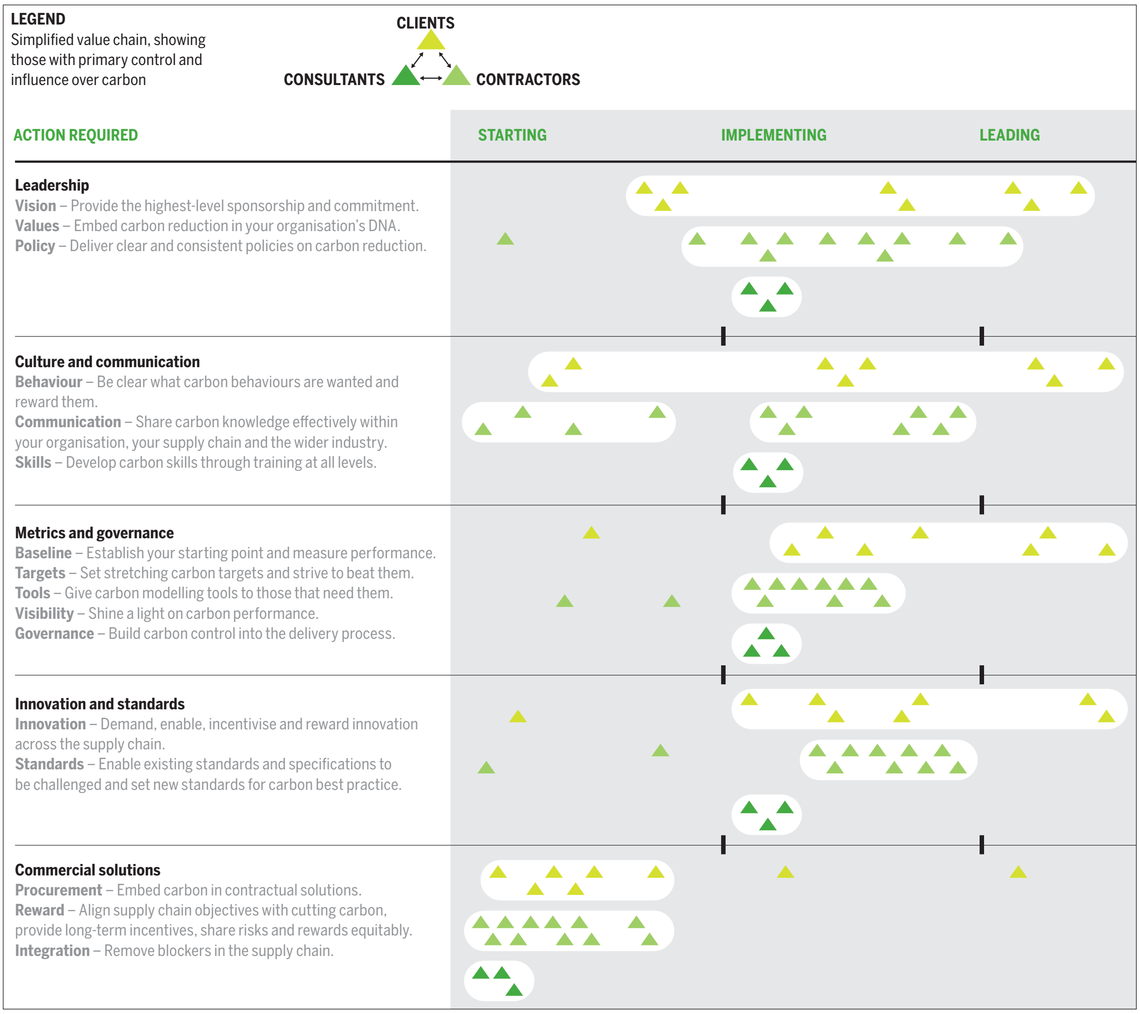
The review placed an emphasis on the notion that reducing carbon reduces costs, citing examples from firms such as Anglian Water. The ICR authors claimed that "*if emerging best practice is driven across the infrastructure sector over the coming years… up to 4 MtCO$_2$e/year of capital carbon and 20 MtCO$_2$e/year of operational carbon could be saved by 2050. This represents a net benefit to the UK economy in that year of up to £1.46 billion/year*." The review provided a wealth of guidance for organisations on reducing carbon both internally and along their supply chains, drawing upon best practice from the sector through an extensive set of surveys and interviews. The review also recommended that "*Government and industry clients should work together to make carbon reduction a requirement on all their infrastructure projects and programmes by 2016*". The response from industry was very positive. For example, one of the largest UK consultancies, Mott MacDonald, subsequently committed to "*measuring [carbon] and driving for reductions on every major project on which we work by 2015*" (Mott MacDonald, 2013). This was reflective of their chairman seeing carbon as a "*business-critical issue*" where "*carbon is a proxy measurement of resource efficiency*". Through its development, publication and promotion, the ICR has helped this mind-set slowly gain traction in the industry. By March 2016, the ICR had been endorsed by a total of 53 organisations, primarily clients, consultants, contractors and suppliers.

One year on from the review the GCB published an update on progress, suggesting that 240 ktCO$_2$ had been saved from exemplar projects undertaken by ICR signatories (GCB, 2014a). The update report suggested that 86% of ICR signatories were now measuring carbon but with little consistency in methods or data. The authors suggested that three key challenges remained in releasing the value offered by carbon reduction.

- Advancing commercial models;
- Getting clients to demand carbon reduction, accept innovation and accelerate the pace of change;
- Setting standards for carbon measurement.

The update also encouraged firms to gauge their level of 'carbon maturity' using a simple matrix (see Figure 1). Progress to date suggested that, whilst firms were implementing changes in culture and developing innovations, few commercial solutions were being adopted (GCB, 2014b).

Figure 1: UKGBC Infrastructure Carbon Review carbon maturity matrix (GCB, 2014b)



The inconsistency in the measurement and management of carbon noted in the ICR led to the Construction Industry Council commissioning the development of a common British Standard PAS 2080 - Carbon Measurement and Management in Economic Infrastructure. Currently under development by Arup and Mott MacDonald, it is anticipated that BSI will publish the standard in May 2016. PAS 2080 is expected to standardise the means of measuring and managing carbon throughout the value chain, and motivate reductions in both carbon and cost. This follows on from the 2008 release of PAS 2050 - Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. PAS 2050 was the first carbon footprinting standard of its kind and is now widely used to assess the carbon impact of goods and services.

The development of PAS 2080 is emblematic of the changes in the construction industry's approach towards sustainability throughout the last three decades. The succession of reviews and reports previously described, combined with increased demands from clients and changing societal attitudes towards climate change have motivated substantial changes in industry attitudes and practices. This progress is neatly summarised by Charles Kibert (2007):

"Since its onset about 15–20 years ago, the contemporary built environment sustainability movement has certainly had an effect on attitudes and practices. A decade ago in developed countries there were few rating systems, products, tools, or publications supporting sustainable construction. Now there is an abundance of resources that provide services, information, and execution support for 'green' projects. A decade ago there was scant knowledge about this new field. Today general knowledge about it is fairly commonplace, while strategies for resolving the major problems of buildings and their impacts remain elusive."

1.4.6 Addressing recurring criticism

In spite of this progress, successive strategic reviews from Egan through to Construction 2025 exhibit a number of recurrent criticisms. Throughout these reports – and over a dozen other intervening reports addressing the inefficiency of the UK construction industry – there is a persistent perception of the industry as wasteful and uncooperative. It could be argued that the persistence of this reputation reflects one of three realities. Either the industry performs more effectively than it appears from the outside; the recommendations have been poorly implemented; or the expectations are unrealistic. In this author's opinion it is likely a combination of all three.

In 2003 Pearce lamented the lack of data allowing effective international comparison and progressive benchmarking of industry performance, yet despite concerted efforts this remains a problem (Pearce, 2003). In fact a general lack of robust data relating to the industry's performance and environmental impacts is a recurring theme throughout the remainder of this thesis. This lack of good quality data has restricted the ability to assess the collective industry objectively, and resulted in perceptions that are governed by individual experiences and interpretations of best and worst practice. Whilst recommendations from each review have been implemented in part, they have rarely been implemented in full. For example, the recommendations highlighted from the IGT report are two of many yet to be implemented. There has also been a fundamental failure to provide strong financial drivers, such as the carbon price advocated by the ICE. The industry also failed to exploit the opportunity for wholesale change provided by the financial crisis, in the manner described by Wolstenholme.

In spite of these failures, the successive strategies intended to motivate change in industry practice have exhibited many of the essential characteristics of a good strategy. They have all contained strong critical reflection; engaged stakeholders throughout the development process; defined intermediate objectives and goals;

focussed on producing actionable content and specified means to achieve the ends. Consequently they have, by and large, garnered strong support from the industry. However, these strategies have consistently suffered from poor execution and a lack of subsequent progress evaluation.

Strategy execution has been repeatedly undermined by changes in Government policy and personnel. No fewer than 12 different ministers have been responsible for the construction portfolio since publication of the first Egan report. This merry-go-round of ministers have been tasked with implementing repeated and often sudden changes in policy, discussed further in Section 2.3.1. The constantly changing nature of construction policy has clearly undermined industry confidence, investment and progress towards strategic targets. For its part, the industry has also failed to recruit and retain a suitably skilled workforce, and displayed a repeated reticence to go beyond the minimum requirements stipulated by regulators. Often large parts of the industry have failed to enter into the spirit of regulatory changes, instead viewing them as a succession of obligations to be met by means requiring the least deviation from current practice. Meanwhile headline targets are frequently changing and historic targets are abandoned. In instances where progress towards interim targets has been monitored and found insufficient – such as the Strategy for Sustainable Construction's targets for on-site emissions – the response has been to cease publication of statistics rather than to investigate and implement further changes.

Throughout this process, the boundary of construction strategy has evolved from a broader focus on sustainability to a narrower and deeper focus on carbon. This focus on carbon has centred on emissions associated with operational energy use in buildings. However, there are signs that this focus is set to change. Both the GCB Routemap and the ICR reasserted the need for a more holistic perspective and emphasised that embodied carbon must start to be addressed in tandem with operational emissions. The following section considers embodied carbon's place in this evolving definition of sustainable construction.

1.4.7 The changing definition of sustainable construction

The terms 'sustainability', 'sustainable construction' and 'green buildings' have now been common parlance for decades. Yet their precise definition remains a source of much debate. By the late 1990s, Palmer et al. (1997) suggested that 'sustainability' had already become a fuzzy buzzword, "*widely used but rarely defined by consensus*". It "*means different things to different people, yet appears to unite them under what is actually a (falsely) shared banner*". Similarly, despite the absence of a largely shared definition, the use of the term 'sustainable building' is rapidly increasing (Berardi, 2013).

Dimensions of sustainable construction

In the construction industry sustainability can incorporate environmental, social or economic dimensions and encompass a host of different considerations and practices. The diversity of issues involved can be observed in this example list from the Holcim Foundation (2014):

"Sustainable construction involves issues such as the design and management of buildings; materials performance; construction technology and processes; energy and resource efficiency in building, operation and maintenance; robust products and technologies; long-term monitoring; adherence to ethical standards; socially-viable environments; stakeholder participation; occupational health and safety and working conditions; innovative financing models; improvement to existing contextual conditions; interdependencies of landscape, infrastructure, urban fabric and architecture; flexibility in building use, function and change; and the dissemination of knowledge in related academic, technical and social contexts."

Other organisations, such as the International Council for Research and Innovation in Building and Construction, have set out whole documents of principles for sustainable building, as part of their vision for 'sustainable, smart eco-buildings' (CIB, 2010). Academic authors have attempted to summarise this multitude of considerations, defining a sustainable building simply as "*a healthy facility designed and built in a cradle-to-grave resource-efficient manner, using ecological principles, social equity, and life-cycle quality value, and which promotes a sense of sustainable community*" (Berardi, 2013). However, it is rare that such a broad and all-encompassing definition of sustainability is adopted in practice. Often sustainability is treated superficially, with the omission of certain elements or the imposition of an implicit hierarchy through the use of selective metrics. Often the maxim of 'what gets measured, gets managed' is too strictly obeyed, resulting in the failure to manage those issues that cannot be readily measured. Even amongst those issues that can be measured, it is clear that energy use has emerged as the contemporary *de facto* metric for the sustainability of a building (Berardi, 2013).

A prescient 2007 editorial of the journal Building Research and Information focussing on the future of sustainable construction, argued that "*it is likely that the dominant measuring stick for all aspects of sustainable construction will be energy*" and that "*the emphasis on energy as an arbiter of directions and value will increase and accelerate in the future*" (Kibert, 2007). This has undoubtedly been the case with subsequent EU and UK political goals and regulations principally focussing upon the energy performance of buildings in operation. These goals have been adopted as part of broader carbon reduction strategies, with energy increasingly used as a proxy for carbon emissions. Lovell et al. (2009) have argued that this greater convergence of energy and climate change goals comes at the expense of wider considerations of sustainability. Similarly, Moncaster (2012) suggests that the "*growing concern about climate change seems to have replaced the discourse of 'sustainability' with a more narrow one of 'carbon*'". This political interpretation of sustainability has in turn led to a narrow focus on addressing operational energy through technical solutions. As a consequence, measures to promote sustainability are too often limited to the greater adoption of low-carbon energy technologies and fabric solutions that improve operational energy efficiency. Meanwhile, only a minority of industry practitioners consider embodied carbon a key element of sustainable construction and are actively engaged in its measurement and mitigation.

Green buildings

'Green buildings' are often considered to be synonymous with, or a subset of, 'sustainable buildings'. This equally nebulous term has proliferated with the rise of sustainability assessment methods and rating systems, such as BREEAM and LEED, and the growth of networks that share best practice and terminologies nationally and internationally. Key amongst these was the growth of national green building councils (GBC), starting with the USGBC's foundation in 1993. The USGBC's LEED building assessment system launched as a rating tool in 1994, and has since become "*a quasi de facto standard defining green building in the US*" (Kibert, 2007). The UK equivalent BREEAM, launched in 1990, and has achieved similar success. These voluntary building assessment systems have now become **the** framework of reference to assess the sustainability of buildings (Berardi, 2013), with over 1.2 billion square metres of building space registered by such systems (WGBC, 2014b). Unfortunately embodied carbon remains a minor component of these systems, as discussed in Section 2.3.2. Numerous countries followed the US example of establishing a GBC, ultimately resulting in the foundation of the World Green Building Council (WGBC) in 2002. This umbrella organisation now includes members from over 100 countries and some 27,000 organisations (WGBC, 2014b).

The UKGBC launched in 2007. This was largely in response to the 2004 Sustainable Building Task Group Report, which called for the "*advisory bodies concerned with sustainable buildings to be simplified and consolidated to provide a clear direction for industry*" (Sustainable Buildings Task Group, 2004). UKGBC initially launched with 36 members but has now grown to over 450 member organisations, including all the major industry players. This growth has reflected changing attitudes within the industry and the shift in client demands towards more sustainable buildings. As noted by Rab Bennetts at the UKGBC launch, "*the climate of opinion has changed. Demand will force us to come up with these things*" (Seager, 2007).

In recent years, client perceptions have changed from green being seen as an optional extra to a standard feature. As neatly put by the Australian GBC, "*whereas developers, owners and tenants used to ask "why go green?" Now, if a non-green building is proposed, they would ask "why isn't it green?"*" (Green Building Council Australia, 2008). Better building performance and environmental credentials are now expected, with green "*just part of what good 'quality' means*" (WGBC, 2013).

Similarly, sustainability has increasingly moved from an issue of principle to an issue of profitability and value retention. In addition to Corporate Social Responsibility (CSR) obligations and reputational benefits, a growing number of clients are motivated by a broadening of the business case for green building, discussed further in Section 2.3.5. Whereas once the business case focussed solely on perceived savings in operating costs, now it has expanded to incorporate increased workplace productivity, improved occupant health and well-being, increased marketability and asset value (WGBC, 2013). This emergent business case is slowly redefining the common conception of sustainability, widening it once more from the narrow focus on energy consumption. This encouraging trend suggests that the dominant contemporary interpretation of sustainability is by no means immutable. As these more holistic assessments of sustainability become routine, this new trajectory not only offers the opportunity to reconsider the social and economic value of buildings, but to revisit the full carbon implications of the building life cycle extending beyond energy consumption in use.

There is evidence from recent industry events, such as the 900+ attendees at the UKGBC's inaugural Embodied Carbon Week (UKGBC, 2014a), that progressive clients and practitioners are starting to view embodied carbon as a key element of sustainable construction. A nascent embodied carbon community is forming, intent on ensuring a prominent role for embodied carbon in any future interpretation of sustainable construction. Whilst this interpretation may spread easily throughout a minority club, it is unlikely to spread to the wider industry without a more robust business case or the introduction of regulatory requirements or incentives.

1.5 Research rationale

As highlighted in the previous sections, the UK Government has ambitious carbon reduction targets both nationally and for the construction sector. If these strategic targets are to be met it is important that embodied carbon becomes a key part of any future interpretation of sustainable construction. If this is to happen then a clear economic and environmental case must be presented. However, to date, a number of elements of this case remain unclear.

The distribution of embodied emissions along the construction sector's complex supply chains requires exploration. It is unclear what range of alternative materials, technologies and practices present the best opportunity for reducing embodied carbon. There is also patchy understanding of the barriers to adoption of these alternatives. It is unclear what levels of embodied carbon reduction are required both in aggregate, and more crucially, at a project level. There is no means of linking sector level reduction targets with project level targets for design teams. There have been few meaningful proposals for an effective short or long-term policy response through regulatory requirements or incentives. A number of practical issues must also be overcome in standardising the approach to embodied carbon assessment, data gathering and interpretation.

A greater understanding of all these elements is critical in forming a credible plan for embodied carbon reduction. The following sections outline the research aims and objectives of this thesis and their contribution towards a credible plan. Subsequent sections introduce the main methodologies employed and set out the structure of the thesis.

1.6 Research aims and objectives

The overarching aim of the research presented in this thesis is to understand what role embodied carbon abatement could have in meeting the UK's medium term sectoral and long term national carbon reduction targets. Within this broad aim there are a number of more specific aims and objectives set out in the following pages. Table 2 on page 26 summarises these aims and indicates by what means and where in the document they are addressed.

The construction sector undertakes a broad range of activities to produce a highly diverse output and depends upon a complex supply chain that spans international borders. Any analysis of embodied carbon in construction must therefore begin with an investigation of the origin, magnitude and distribution of emissions across these activities and supply chains. Such an analysis can be adopted from a number of perspectives, whereby emissions are attributed to a final product, e.g. houses, offices, factories etc., an intermediate activity, e.g. raw material extraction, material manufacture, transport to site etc., or by spatial origin e.g. emissions arising in the UK, EU, China etc. All of these perspectives are pertinent in understanding the mitigation potential. Understanding the impact of final products reveals the potential for mitigation through changing demand patterns, e.g. reducing the number of new offices constructed. Understanding the relative impacts of intermediate actions can highlight carbon hot-spots or intervention points with the greatest reduction opportunities, e.g. key materials or processes where one change could yield substantial reductions. Finally, with climate policy determined independently at company, sectoral, national, and international levels, an understanding of the spatial origins of emissions is critical in formulating an appropriate policy response. Only two prior attempts have been made to estimate the embodied emissions attributable to UK construction (BIS, 2010; GCB, 2013b), both of which considered only the intermediate activity perspective and suffered from limitations described in the following chapter. Therefore the first research aim is to:

Conduct a robust evaluation of the embodied carbon emissions associated with the UK construction sector supply chain

Within this aim the objectives are to:

» Develop a time series of annual embodied emissions of the construction sector.
» Evaluate the embodied emissions from multiple perspectives; namely: by final product, intermediate activity and spatial origin.

From this evaluation, a number of priority sources of embodied emissions are revealed; the largest of which are emissions from materials extraction, manufacture and production. Emissions from transport and construction activities are also notable and can be reduced through measures such as using low emission vehicles to transport materials and the efficient use of construction plant (Ko, 2010). However, as the majority of embodied emissions are associated with the production of core building materials, substantial embodied carbon reduction will only be achieved through improvements in material manufacture or a reduction in the use of those materials with the most carbon-intensive supply chains. The construction sector has limited influence on the manufacturing processes of key materials such as steel and cement. Both academic authors and industrial roadmaps have suggested that there is minimal scope for significant emissions reduction in the manufacture of these materials in the short-medium term as production processes are already highly efficient and, in some cases, are approaching practical and thermodynamic limits (Allwood & Cullen, 2012; WSP et al., 2015b; WSP et al., 2015a). Consequently, opportunities to minimise emissions primarily involve reducing the use of these materials. The construction sector can achieve this through the adoption of a variety of alternative materials, technologies and practices (Cabeza et al., 2013). The numerous options include: substituting materials derived from naturally occurring renewable substances; materials that incorporate wastes or recycled content; materials that have been repurposed or sourced for re-use from other sites; and construction products that have been optimised through novel production techniques. Some of these options are doubtless more practicable than others. Consequently, the second research aim is to:

Use the literature to appraise options that could deliver substantial reductions in the use of construction materials with carbon-intensive supply chains

Within this aim the objectives are to:

» Identify the alternative materials, technologies or practices which could substantially reduce the demand for carbon-intensive materials in the construction sector.
» Assess the suitability of such alternatives in a UK context. i.e. could they be adopted in a timescale that is compatible with UK climate targets and subject to acceptable social, economic and environmental trade-offs?

The appraisal of options reveals a wide variety of alternative materials are available. However, whilst there are many examples of their successful use, there remain a multitude of barriers to widespread adoption of alternative materials amongst practitioners involved in the design and construction process. Many of these barriers are not associated with technical performance but with perceptions or cultural norms within the industry. However, as highlighted by Watson. et al (2012), minimal qualitative work assessing these barriers has been completed. Understanding the barriers to adoption of alternative materials requires not only determining what must be done to demonstrate performance and gain acceptance but also an understanding of the root causes of the resisting behaviour and conservatism of industry practitioners (Jones et al., 2015). Therefore the third research aim is to:

Conduct new research to understand the cultural, behavioural, and perceptual barriers to adoption of alternative low carbon building materials amongst industry practitioners involved in design, specification and construction

Within this aim the objectives are to:

» Identify the barriers to initial adoption and widespread uptake of a selection of example low carbon building materials.
» Explore the underlying industry structures and practices that support these barriers.
» Identify measures which could accelerate the adoption of low carbon building materials.

In response to a growing interest in embodied carbon, the industry has recently engaged in a variety of data gathering efforts, such as the public WRAP Embodied Carbon Database (WRAP & UKGBC, 2014), which allows users to share building level life cycle assessments (LCAs). Schemes such as this and published benchmarks from groups such as the RICS (2012), are facilitating relative performance assessment between designs. However, this bottom up data has yet to be integrated with top down data representing overall sector output. This integration is crucial for design teams and policy makers to assess not only performance relative to their contemporaries, but absolute performance in the context of UK climate mitigation strategies. In the long term it is essential that a link is formed between sector level reduction targets and the tangible project level benchmarks utilised by design teams. This is the only way in which current performance can be assessed and the scale of future requirements determined. Without this link it is impossible for policy makers to determine the adequacy of any proposed policy intervention, such as extending regulation restricting operational carbon to include embodied carbon. Therefore the fourth research aim is to:

Create an analytical framework for translating sector emission reduction targets into project level targets, suitable for use by design teams

Within this aim the objectives are to:

- Develop a UK Buildings and Infrastructure Embodied Carbon Model (UK BIEC) that integrates emissions outputs from a top down sector level model with a database of bottom up building level LCAs.
- Explore the means by which such a model could facilitate future assessment of progress towards sector reduction targets and the setting of project targets.

The creation of such a model also facilitates scenario analysis, a means commonly used to appraise possible futures and responses. In addition to changing patterns in material demand, a key strategy in reducing embodied carbon could be minimising aggregate demand for new buildings and infrastructure. By contrast, current Government strategies and industry projections assume significant growth in industry output over the coming decades in key areas such as housing and infrastructure. This additional output has the potential to drive growth in embodied carbon and restrict the ability of the industry to achieve sector carbon reduction targets in absolute terms. In essence: the greater the growth in construction activity, the less carbon-intensive that activity must be. Thus, significant growth in overall activity implicitly imposes more severe carbon reduction targets at a project level, necessitating the adoption of a different range of reduction strategies. In an attempt to shed light on the impacts of this projected growth in demand, the fifth research aim is to:

Use the new framework to explore the role for demand reduction in meeting embodied carbon reduction targets

Within this aim the objectives are to:

- Formulate a series of scenarios that reflect plausible future levels of demand for new building and infrastructure stock.
- Evaluate the embodied emissions implications of these scenarios in relation to sector and national carbon reduction targets.

In addition to demand side responses, there is space for additional drivers of supply side responses, be they industry-led agreements or regulatory requirements and incentives. Industry practitioners have already begun to discuss potential avenues for regulation of embodied carbon through events such as the Alliance for Sustainable Building Products (ASBP) 'Embodied Carbon: Why, how and when? Debate', hosted in April 2014. A group of practitioners also formed a self-titled Embodied Carbon Task Force in 2014, which lobbied for inclusion of embodied carbon as an Allowable Solution under the proposed Zero Carbon building regulations (Battle, 2014). As local authority requirements and international precedents for regulation of embodied carbon emerge, there is a clear need for an appraisal of potential policy responses. These responses must also be situated within a longer pathway towards a low carbon construction industry. The policy response to operational emissions has been introduced gradually through the introduction of new regulation and a ratcheting up of existing policies. It is likely that embodied carbon will require a similar measured and progressive response. This response must also be responsive to changing targets for carbon mitigation and resilient to the shifting political landscape responsible for a turbulent regulatory environment. Consequently, it may be of benefit to position potential policy options within a range of dynamic adaptive policy pathways (Haasnoot et al., 2013). Such pathways would retain the flexibility to respond to changing circumstances, technologies and ambitions whilst highlighting critical short term actions and key decision making points. To this end the final research aim is to:

Identify possible policy responses and industry-led actions that could motivate substantial embodied carbon reduction

Within this aim the objectives are to:

- Assemble a list of possible policy responses and industry actions to reduce embodied carbon.
- Develop an initial set of dynamic adaptive policy pathways through a participatory approach with key stakeholders.
- Highlight critical short term actions and key decision making points for policy makers.

Recent high profile reports and initiatives, such as the introduction of the RICS methodology for calculation (RICS, 2012), the ICR (HM Treasury, 2013) and the UKGBC's inaugural Embodied Carbon Week (UKGBC, 2014a) reflect the construction industry's growing ambitions to reduce both operational and embodied carbon. The GCB Low Carbon Routemap for the Built Environment constituted a first attempt to translate these ambitions into tangible sector goals that are compatible with national emission reduction targets (GCB, 2013b). However, as a result of focussing the bulk of project resources on operational emissions, the final recommendations only amounted to a first step towards determining a viable sector plan for embodied carbon. Furthermore, whilst the Routemap listed some potential solutions it did not address the barriers to adoption of low embodied carbon alternatives or propose a meaningful policy response. In aggregate, the research objectives presented here, represent a further step towards forming a credible, coherent and resilient plan for reducing embodied carbon. The following section elaborates on the methodologies used in meeting these objectives.

1.7 Research methodologies

The problems faced by researchers exploring opportunities to reduce carbon emissions within the built environment do not sit exclusively within one discipline. These problems interest academics from a diverse range of fields spanning building physics to anthropology; not to mention a range of industrial practitioners. Whilst a variety of disciplines can offer different insights, a deeper understanding can only be achieved from an interdisciplinary perspective. Although the author’s background is in the more technically focussed discipline of engineering, this thesis draws upon a mix of methodologies from economics and the social sciences. These more qualitative and, in some cases, abstract approaches are underpinned throughout by a sound understanding of the engineering principles and practicalities. The methodologies are briefly described in turn below, with a more detailed description and justification presented at the start of each chapter. A broad overview of the research aims, their corresponding methodologies and the thesis structure can be seen in Table 2 on page 26.

The evaluation of embodied emissions associated with the UK construction sector supply chains draws primarily upon input-output modelling. This well-established economic accounting approach deals with the connections between industry sectors and households in a national economy in the form of supply and consumption of goods and services, formation of capital, and exchange of income and labour. It employs the methods developed by Wassily Leontief to transform national accounts data into an analytical framework consisting of a series of equations which each describe the distribution of an industry’s product throughout the economy, see Miller & Blair (2009) for an overview. Increasingly this technique been used to tackle environmental problems, generally through linking environmental pressure data to financial transactions within an economy, in order to allocate impacts to particular products or sectors (Minx et al., 2009). In this instance a multi-regional framework is extended to incorporate carbon emissions in order to enumerate the full emissions associated with the UK construction sector’s network of international supply chains.

The appraisal of options for embodied carbon reduction, and the initial assessment of barriers to their adoption, is formed from a review of the existing literature. Whilst not constituting a full systematic review, as typically conducted in medical research, the review attempts to identify, appraise, select and synthesize available research on the topic within a pre-defined framework according to a review protocol. By this means an evidence base was gathered from an extensive literature search of academic publications, supplemented by data and publications from trade bodies and other non-academic sources. This evidence base was filtered using relevance ratings prior to review and the key features of each low carbon alternative, and the barriers to their adoption, were extracted and synthesized.

Further research assessing common barriers to the adoption of low carbon materials adopted a qualitative mixed method approach combining a survey and series of semi-structured interviews. A sequential explanatory design was selected, whereby a survey would gather initial quantitative and qualitative data on the barriers to adoption, followed by interviews exploring the identified barriers in greater depth. All interviews were recorded and transcribed. Transcriptions were then coded and analysed according to a thematic framework. This approach is commonly used across a range of disciplines, see Tashakkori & Teddlie (2003), and was selected to provide the desired combination of breadth and depth.

The development of a framework for translating sector emissions reduction targets into project level targets necessitated the development of a new quantitative UK Buildings and Infrastructure Embodied Carbon model (UK BIEC). UK BIEC integrates output from a multi-regional input output model with a database of building level life cycle assessments. The combination of these top-down and bottom-up data sources represents a novel modelling approach within this sector. The advantages and limitations of such an approach are discussed at length in Chapter 6. Scenario analysis is subsequently used to enumerate the influence of demand for new building stock and the role for design and material changes in meeting sector emission reduction targets. Scenario analysis is a commonly used analytic tool within this field for exploring the range of possible future outcomes.

The development of potential policy pathways adopted a participatory approach using a stakeholder workshop alongside informal interviews and discussions. An initial shortlist of potential policy responses and industry-led actions was developed from available literature, then expanded upon through the stakeholder workshop. The resultant options were provisionally assembled into pathways using the approach proposed by Haasnoot et al (2013). Critical reflection upon the approach during discussions at the stakeholder workshop identified potential opportunities to adapt and improve the methodology for this novel application. See Chapter 7 for further discussion.

1.8 Thesis organisation and structure

The thesis is organised into eight chapters, supplemented by a bibliography and several appendices.

Chapter 2 discusses regulatory and client-led drivers for carbon reduction and summarises current practice in embodied carbon assessment.

Chapter 3 critiques past estimates of aggregate sector embodied emissions and presents a new estimate, including analysis from multiple perspectives.

Chapter 4 provides an overview of the main design strategies, alternative materials and business models that could reduce the construction industry's dependence on materials with carbon-intensive supply chains.

Chapter 5 explores the barriers to adoption of these alternative materials, presenting results from a survey and series of practitioner interviews.

Chapter 6 discusses the challenges involved in integrating sector emission reduction targets with project level embodied carbon targets and introduces the new UK BIEC model. Scenario analysis is used to explore the role for demand reduction and the implications of future demand for building stock on project level embodied carbon targets.

Chapter 7 discusses the policies and industry-led actions that could support substantial embodied carbon reduction. Possible responses are positioned within adaptive policy pathways developed through a participatory approach with key stakeholders.

Chapter 8 concludes by drawing together the findings from preceding chapters and highlighting avenues for future work.

Table 2: Summary of research aims, methodologies and thesis structure

Chapter	Research aims	Methodologies
1	*Sets out project aims and thesis structure*	Literature review
2	*Provides necessary background information*	Literature review
3	Conduct a robust evaluation of the embodied carbon emissions associated with the UK construction sector supply chain	Multi-regional Input Output modelling
4	Use the literature to appraise options that could deliver substantial reductions in the use of construction materials with carbon-intensive supply chains	Literature review
5	Conduct new research to understand the cultural, behavioural, and perceptual barriers to adoption of alternative low carbon building materials amongst industry practitioners involved in design, specification and construction	Qualitative mixed method approach combining a survey and series of semi-structured interviews
6	Create an analytical framework for translating sector emission reduction targets into project level targets, suitable for use by design teams	Hybrid modelling
	Use the new framework to explore the role for demand reduction in meeting embodied carbon reduction targets	Scenario analysis
7	Identify possible policy responses and industry-led actions that could motivate substantial embodied carbon reduction	Literature review and participatory approach with key stakeholders
8	*Summarises conclusions*	

2. Carbon emissions in the built environment

> *A trend that may be observed is the increasing proportion of embodied emissions that is one consequence of efforts to decrease operational emissions. This implies that global efforts to reduce emissions in buildings cannot be totally achieved by ignoring the emissions embodied in buildings.*
>
> Ibn-Mohammed, Greenough, Taylor, Ozawa-Meida, & Acquaye, 2013

2.1 Introduction

The assessment of carbon emissions in the built environment is becoming increasingly commonplace. A growing community of building product manufacturers, architects, engineers, quantity surveyors, sustainability consultants and academics are engaged in increasingly complex efforts to estimate carbon emissions incurred throughout the building life cycle. Whilst the assessment of emissions incurred in a building's operation has become routine, the assessment of emissions incurred in product manufacture, construction, maintenance, refurbishment and end of life disposal remains the preserve of a minority of industry practitioners. This chapter considers the reasons for this, providing a review of current drivers for carbon reduction and typical practice in embodied carbon assessment.

The chapter is divided in two halves, the first of which reviews regulations and client requirements that promote embodied carbon reduction. The second half provides an overview of current typical and best practice in embodied carbon assessment at both the product and project level. The range of methodologies employed, their limitations, and common practical challenges encountered in assessments are briefly summarised and the shifting balance between embodied and operational emissions across the building life cycle is highlighted.

The chapter commences with a brief description of the research objectives, boundaries and methodologies applied in the remaining sections. Section 2.3.1 reviews existing regulation promoting carbon reduction at a European, national and local authority level in turn. Section 2.3.2 discusses associated voluntary initiatives and Section 2.3.3 outlines comparable international developments. Section 2.3.4 discusses the collective shortcomings of past and present regulations. Section 2.3.5 introduces client-led drivers for carbon reduction, briefly reviewing some examples of current requirements and the associated business case.

Section 2.4.1 depicts current practice in embodied carbon assessment at the project level. Section 2.4.2 depicts practice at the product level, including a review of the principal LCA methodologies. Sections 2.5 and 2.6 outline the changing balance between operational and embodied emissions and make the case for further measures addressing embodied carbon. Section 2.7 draws together the preceding sections to discuss the adequacy of existing drivers and practices in achieving strategic carbon mitigation targets.

2.2 Research methodology, objectives and boundaries

The objective of this chapter is to provide an overview of current practice and drivers for embodied carbon assessment. This is intended to provide context for readers unfamiliar with the UK industry and an overview of methodologies and terminology used in later chapters. The objective is met through a conventional literature review, drawing upon recent academic and grey literature. The chapter also includes an overview and critique of current UK policy.

The review of current practice focuses on the assessment of embodied carbon emissions and does not consider the assessment of operational emissions in any depth, as this has been covered at length elsewhere. However, the review of policy does consider all major policies aimed at carbon reduction across the building life cycle, with an emphasis upon embodied carbon. The review also focuses upon embodied carbon assessment in buildings, as opposed to infrastructure assets – where current practice is more advanced. Though some examples are drawn from the infrastructure segment of the industry where relevant.

2.3 Drivers of carbon reduction in the built environment

Changes in construction practice have historically been driven by a combination of client demands and regulation. This has typically taken the form of financial incentives or minimum requirements imposed at a European, national or local authority level. These minimum requirements are supplemented by more ambitious targets in the client brief. Client demands are often expressed through ratings against general sustainability assessment schemes, such as BREEAM, or through specific KPIs. In recent years, the budding CSR ambitions of construction firms have also led to participation in various common voluntary initiatives aimed at reducing environmental impacts. Thus the combination of regulation, voluntary initiatives, and client demands determines project requirements and ambitions. The following sections review these drivers for carbon reduction in turn, starting with regulation.

2.3.1 Regulation promoting carbon reduction

Whilst over recent years the construction industry's capacity to deliver low carbon buildings has improved, client demand and willingness to pay has not kept pace. A perceived lack of demand, and the split incentives created by the industry structure, has left many construction firms without sufficient market drivers to promote low carbon building. Consequently, within the industry, regulation is seen as the principal driver of low carbon building, both new build and retrofit. Indeed the IGT Low Carbon Construction report concluded that "*the almost universal perception in the industry is that only regulation will create mass demand*" (HM Government, 2010). This is particularly the case in certain areas of the market, such as housing, where it has been repeatedly suggested that "*without Government intervention, it is unlikely that the majority of housebuilders – left to their own devices – would do much to deliver any form of sustainability*" (Calcutt, 2007 p. 184). Consequently, the past decade has been peppered with a succession of policies motivating carbon reduction. The majority of these have focussed on addressing operational emissions through the uptake of energy efficiency measures and harnessing renewable sources of energy. Limited steps have also been taken towards addressing full life cycle emissions, including emissions embodied in materials and construction waste. This section briefly summarises the key policies at a European, national and local authority level.

2.3.1.1 European regulation

In recent years the European Commission (EC) has increasingly focussed on the twin goals of resource efficiency and developing a more circular economy. Both of these ideals have become flagship elements of the overarching Europe 2020 Strategy and the subject of respective roadmaps (EC, 2011; EC, 2015a). Whilst directives released in the early years of the 21st century, such as the Energy Efficiency Directive, Energy Labelling Directive and the Eco-design Directive focussed on promoting energy efficiency and renewable energy use, recent communications have focussed on broadening the considered range of environmental impacts and providing complementary policies for material and resource efficiency. For instance, a key milestone of the Resource Efficiency Roadmap stipulates that by 2020 all buildings will be "*highly material efficient*" and life cycle approaches will be "*widely applied*" (EC, 2011 p. 18). An increasing emphasis has been placed on minimising construction and demolition waste; whilst promoting life cycle costing and the use of sustainable materials. This has been reflected in the recent Construction Product Regulations and the Waste Framework Directive; which includes targets such as 70% of non-hazardous construction and demolition waste to be recycled by 2020 (EC, 2008). This trend towards a greater focus on resource efficiency is in part motivated by ambitious European GHG reduction targets, which have given rise to a number of headline interventions, such as the introduction of the European Union Emissions Trading Scheme (EU ETS). Further anticipated developments were set out in a Communication on Resource Efficiency Opportunities in the Building

Sector (EC, 2014), discussed further in Section 2.3.3. Although a strengthened Circular Economy Package is anticipated in the near future, at the time of writing, the principal European driver of carbon reduction in the built environment remains the Energy Performance of Buildings Directive (EC, 2002).

Energy Performance of Buildings Directive

The Energy Performance of Buildings Directive (EPBD) first published in 2002, required member states to develop a methodology for calculating and certifying the energy performance of buildings and to place minimum requirements on the performance of new buildings and those subject to major renovation. A recast EPBD was adopted in 2010, which stipulates that all new buildings must be nearly zero-energy by the end of 2020 (and by the end of 2018 for public buildings) (EC, 2010). The definition of nearly zero-energy implies both "*very high energy performance*" and that "*the low amount of energy required should be covered to a very significant extent by energy from renewable sources*". However, this target is subject to the proviso that "*requirements should be set with a view to achieving the cost-optimal balance between the investments involved and the energy costs saved throughout the lifecycle of the building*" (EC, 2010). The UK response to the recast EPBD was to propose a raft of national policies including Energy Performance Certificates (EPC), changes to Part L of the Building Regulations and the 'Zero Carbon Homes' and equivalent non-domestic targets.

2.3.1.2 National regulation

Recent years have seen numerous reviews and high profile changes to UK construction policy. The overview below thus includes both current and recently disbanded policies that have shaped current industry practice.

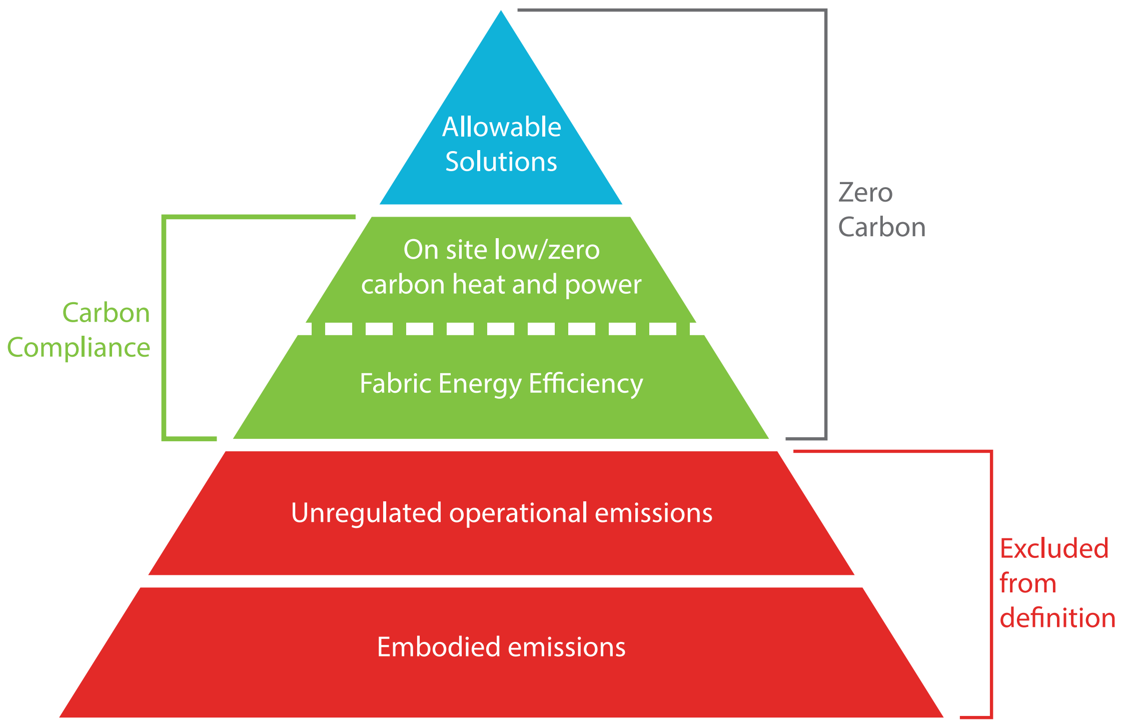
Zero Carbon Buildings

In 2006 the UK Government announced an ambition that all new homes would be 'zero carbon' by 2016 (DCLG, 2006a). This was followed by an announcement in the 2008 budget that all new non-domestic structures be 'zero carbon' by 2019 (with interim targets of 2016 for schools and 2018 for public sector buildings). When the target was announced no detailed definition of 'zero carbon' was available; the broad brush interpretation being that "*over a year, the net carbon emissions from all energy use in the home would be zero*" (DCLG, 2007). DCLG suggested that achieving this would save 15 $MtCO_2$ per year by 2050 (DCLG, 2007). Following a recommendation from the Calcutt Review of Housebuilding Delivery (Calcutt, 2007), the non-profit Zero Carbon Hub was established in 2008 to take day-to-day operational responsibility for delivering zero carbon homes. This organisation was instrumental in developing the definition of zero carbon.

Following consultation, an initial definition of 'zero carbon' was established in 2008 and then swiftly revised. The target would refer only to operational carbon emissions and would take no account of embodied carbon. In the 2011 Budget the definition was further watered down to limit coverage to regulated emissions, excluding unregulated emissions such as cooking and plug-in appliances. In spite of this, the ultimate definition still somewhat disingenuously stipulated that "*all emissions from the structure and the activities that take place within it must be net zero over the course of a year*" (Zero Carbon Hub, 2013). In practice this was intended to require three elements: meeting a Fabric Energy Efficiency Standard (FEES); provision of on-site low or zero-carbon heat and electricity sources; and additional so-called 'Allowable Solutions' (see Figure 2). Effectively, the definition for 'zero carbon' ensured that a minimum standard of building fabric is adopted and that remaining regulated operational emissions are offset through the provision of on or off-site renewable energy solutions. The definition did not limit embodied emissions or unregulated operational emissions. Between them these often account for over half the total life cycle emissions of new build homes.

The exclusion of embodied carbon came in spite of a 2006 public consultation receiving many industry responses stressing the need to include embodied carbon within any proposed definition. Critics have argued that "*the apparently deliberate omission of the embodied carbon from the definition of 'zero carbon' implies a greater political interest in increasing construction than in reducing carbon*" (Moncaster, 2012). Indeed, Moncaster argues that political domination of appointments and the limitations imposed by the terms of reference for the groups developing

Figure 2: Proposed zero carbon definition prior to 2015 announcements (adapted from Zero Carbon Hub 2014)

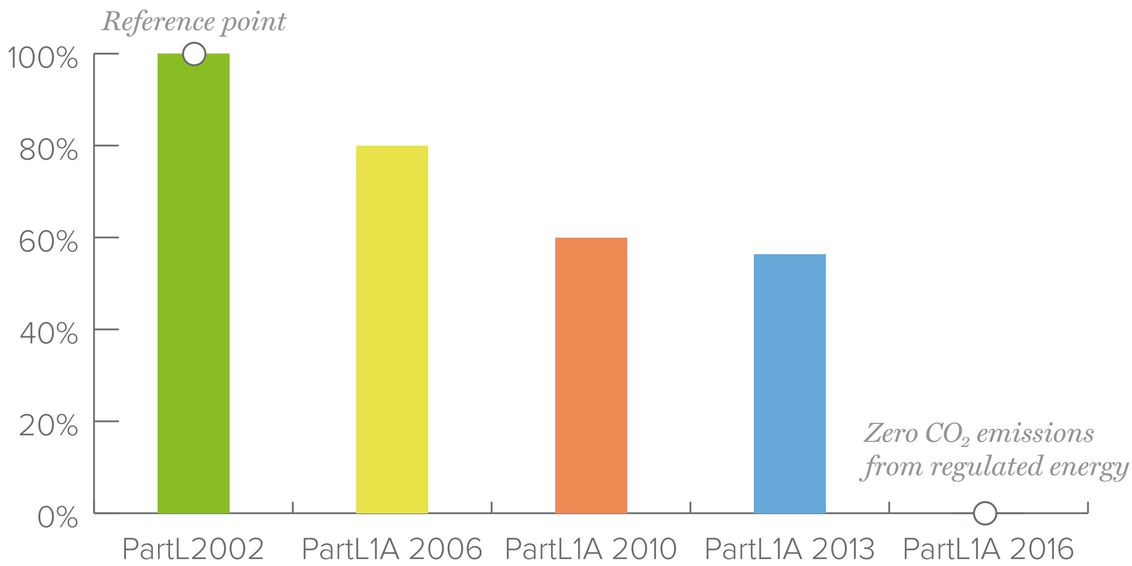


sustainable building policy resulted in a restriction of the issues that were included and represented a deliberate choice to exclude certain industry interests. In response to the omission from the final definition, a group of industry practitioners calling themselves the Embodied Carbon Task Force lobbied to include a range of embodied carbon abatement measures as Allowable Solutions (Battle, 2014).

Changes were introduced in Part L of the Building Regulations in 2010 and 2014 as an interim step towards the Zero Carbon targets (see Figure 3). In 2014 the Government also passed enabling legislation to support Allowable Solutions. Then in July 2015, the newly elected Conservative Government announced that to "*reduce net regulation on housebuilders. The government does not intend to proceed with the zero carbon Allowable Solutions carbon offsetting scheme, or the proposed 2016 increase in on-site energy efficiency standards*" (HM Treasury, 2015a p. 46). This shock announcement was buried amid a package of measures to address the UK's long-term productivity problem. The announcement was decried as "*short-sighted, unnecessary, retrograde and damaging to the house building industry*" (UKGBC, 2015b). Over 200 businesses signed a letter to the Chancellor protesting the changes, claiming that the move "*undermined industry confidence in Government*" and will "*curtail investment in British innovation and manufacturing*" (UKGBC, 2015c). At the time of writing, it remains unclear what aspects of the policy will be pursued in the coming years. The 2020 deadline for implementing the EPBD would suggest that some further improvements will be made in this parliament; however, inaction can be justified where solutions are deemed not to be "*cost-optimal*".

The additional cost of achieving Zero Carbon Homes has been a persistent cause of debate since the target's inception. Calculations by consultancy Sweett in 2006 suggested that a Zero Carbon Home could cost £40,000 more than one built

Figure 3: Proposed PartL1A improvements over time in regulated CO_2 emissions reductions prior to 2015 announcements (Zero Carbon Hub 2014)



to 2006 regulations. Further calculations in 2011 suggested that a semi-detached home would cost only £11,891 more than one built to 2010 energy regulations (Sweett, 2011). Sweett's latest estimates in 2014 suggested a semi-detached home built to the Zero Carbon Homes standard would cost less than £5000 more than one built to current regulations (Zero Carbon Hub & Sweett, 2014). In February 2015, Cardiff University completed the demonstration Solcer House, a net energy-positive house – typical of the sort that would be required to meet the standard as proposed – for under £1000/m^2, within the typical range for social housing (Cardiff University, 2015). This progress suggests that the associated costs of building to the Zero Carbon standard have drastically declined over recent years. In spite of these reductions, the fear of increased costs preventing development and undermining house building targets appears to have diluted political support for the Zero Carbon agenda and resulted in its ultimate demise.

Changes to the Building Regulations

The UK Building Regulations set out legal requirements for building work and are coded by topic from A to Q. The principal amendments expected to deliver the goals of the EU EPBD are to Part L which governs conservation of fuel and power. A range of detailed changes have been enacted over the past 5 years, the main thrust of which is shifting the focus of measurement from elemental U-values to actual CO_2 emissions and progressively tightening performance requirements. The purpose of this technology neutral approach is to encourage improvements through a variety of means but chiefly through a fabric first approach. These changes are the principal driver of improved performance in buildings in England and Wales and were initially viewed as interim steps towards the adoption of Zero Carbon standards. Scotland and Northern Ireland have separate regulations that have been subject to comparable changes.

Since 2006 regulations have required estimation of a Dwelling Emission Rate (DER), representing the annual CO_2 emission rate of the dwelling, as calculated to the SAP procedure. The main changes of interest have been made to the Target Emission Rate (TER) – the limit the DER must not exceed. Changes in October 2010, stipulated that the TER must be 25% lower than in 2006. In April 2014, further changes came into force introducing a Fabric Energy Efficiency Target. The regulations now refer to the Dwelling Fabric Energy Efficiency (DFEE) and the Target Fabric Energy Efficiency (TFEE). The 2014 changes were expected to (across the build mix) achieve a 6% carbon improvement on the 2010 Regulations for domestic buildings and a 9% improvement for non-domestic properties.

Whilst the focus of the regulations has shifted over the last decade to heavily restrict operational emissions, the regulations still do not address embodied emissions. Indeed, it has been suggested that, even if a standard measurement system were adopted and targets established for embodied emissions, such changes could not be incorporated into regulations until 2019 at the earliest (Tebbit, 2013). This would also require political will that is currently lacking.

The Code for Sustainable Homes

Ahead of the adoption of the Zero Carbon targets, the now defunct Code for Sustainable Homes launched as a voluntary standard intended to promote high environmental standards in home building (DCLG, 2006b). It assessed homes on the basis of nine categories of sustainable design* and awarded a rating between 0 and 6 stars (where 6 stars represented an exemplary development). The assessment was initially undertaken at the design stage with certification awarded after construction following a visual inspection. In 2008 it became mandatory for homes to be rated, with the information included within the newly introduced Home Information Packs. This requirement was removed (alongside the Home Information Packs) following the change of Government in 2010. Following the 2014 Housing Standards Review, the Government announced its intention to disband the Code and consolidate many of the requirements into the Building Regulations. The most recent adjustments to the Building Regulations in some respects equate to a Code Level 4 home. Despite the disbanding, up until March 2015 the Code was a mandatory requirement for many Local Authorities or where affordable housing was being funded by the Homes and Communities Agency. These minimum standards were typically set at 3 stars. In March 2015, the Secretary of State for Communities and Local Government confirmed that local authorities could no longer impose Code requirements within the planning process.

Between April 2008 and December 2014, 151,262 dwellings in England, Wales and Northern Ireland achieved a 3 star rating at the post construction stage, with 42,017 achieving 4 stars, and 627 achieving 5 stars (DCLG, 2015a). Throughout the scheme's six years in operation only 306 properties achieved the maximum 6 star standard which constituted the originally mooted definition of a 'Zero Carbon Home'. The overwhelming majority of properties certified under the code were public sector housing, suggesting a reticence from the private housebuilding sector to voluntarily implement high standards (Heffernan et al., 2015).

Building materials formed part of the Code assessment but only contributed a minimal amount to the total score. Up to 4.5 points could be achieved for minimising the environmental impact of building materials (with a further 2.7 points available for responsible sourcing). This represented up to 10% of the points required for a 3 star

*The categories were energy and CO_2 emissions; water; materials; surface water and run-off; waste; pollution; health and wellbeing; management; and ecology. Minimum standards were required to achieve one star or higher for the first 5 categories. Standards were also set for each higher level for energy and CO_2 emissions and water. The others categories were entirely flexible.

building, and only 7% of the points required for a 6 star building. By comparison, 2.4 points could be gained by providing safe bicycle storage, 1.2 points for classifying a room as suitable for a home office, 1.2 points for providing a space to dry clothes, and a further 3.6 points could be gained for providing good recycling facilities (i.e. 3 large bins in a location with a Local Authority collection scheme). Thus, whilst the Code for Sustainable Homes undoubtedly helped to promote sustainable construction and a reduction in operational emissions, it provided minimal incentive for reducing embodied emissions.

Sensing a gap in the market for a voluntary standard, BRE launched a new Home Quality Mark (HQM) in 2015 which seeks to build upon the best aspects of the Code and allow house builders to continue to differentiate themselves in the marketplace. The details of the assessment process were not available at the time of writing.

The Green Deal

The Green Deal was the latest in a long line of attempts to encourage greater uptake of energy efficiency improvements in the UK's ageing building stock. Past schemes to improve domestic energy efficiency, such as the Homes Insulation Scheme (1978-1990) and CERT (2008-2012), have had some success. Estimates suggest that by 2006 energy efficiency measures saved 51% of domestic energy relative to what would have been consumed under 1970 insulation and efficiency conditions (Utley & Shorrock, 2008). Despite this, there remains great scope for further improvement of the UK's existing building stock with an estimated 6.9 million solid wall, 5.8 million cavity wall, 5.7 million top-up loft and 3 million floor insulation projects that could be undertaken. In addition there remain 2 million single glazed properties and 12 million non-condensing gas boilers that could be replaced (DECC, 2012a pp. 35–36). Whilst there is undoubtedly great physical potential to reduce operational emissions from the existing building stock, many of these savings are hard to realise and depend upon the willingness of consumers (Shorrock, Henderson & Utley, 2005). Until mid-2015, The Green Deal represented the Government's primary response to this challenge.

At the time of its launch in autumn 2012, the Green Deal was touted as a flagship policy. Unlike previous schemes, it loaned up front capital to home owners and businesses to install energy efficiency measures, with the cost repaid through long-term savings in energy bills. DECC analysis prior to the launch predicted that, combined with the Energy Companies Obligation (ECO),[**] domestic emissions

**The ECO scheme was introduced in January 2013 to reduce fuel poverty and carbon emissions. It was intended to fund around £1.3bn of energy efficiency measures in hard to treat properties in low-income areas each year until March 2015 (DECC, 2013). ECO effectively replaced the Carbon Emissions Reduction Target (CERT) and Community Energy Saving Programme (CESP).

reductions of 1.5 $MtCO_2e$ would be achieved through 2013-2017 rising to 4.9 $MtCO_2e$ by 2023-2027 (DECC, 2012b p. 26). The non-domestic equivalent was expected to yield savings of 1.2 $MtCO_2e$ through 2013-2017 rising to 4.4 $MtCO_2e$ by 2018-2022. Overall the scheme was initially projected to save nearly 86 $MtCO_2e$ over its lifetime (DECC, 2012a pp. 45–46). This figure assumed 14 million homes receiving retrofit measures by 2020. The embodied emissions of retrofit measures were not considered in these estimates, though research has suggested these would be substantial (Sahagun & Moncaster, 2012).

However, these savings failed to materialise in practice, as in the first six months of the Green Deal scheme only five households signed up. Subsequently it was revealed that of the first 38,259 homes to be assessed, only 241 consented for work to proceed (BBC News, 2013). This rate of uptake was substantially lower than that observed during the trial period (Dowson et al., 2012). Adoption rates increased somewhat over the following year, but by the close of the first 18 months of the scheme only 4,000 plans had been initiated. This total was far short of the 10,000 plans that were predicted for the first 12 months. Critics blamed the unattractive interest rates (7%) and DECC's poor communication strategy for the "*disappointing failure*" of the scheme and called for substantial changes (Energy and Climate Change Committee, 2014).

In June 2014, the Government introduced the Green Deal Home Improvement Fund (GDHIF), designed to work alongside Green Deal finance. The GDHIF allowed householders to claim part finance for certain measures. The full funding of the scheme was exhausted within a month of opening following a large number of applications. Subsequent funding of £30 million was released in December and fully allocated within a day. A further round of funding opened in March 2015. By April 2015, 20,178 households had measures installed using the GDHIF at a cost of £220 million, compared with only 7,817 through Green Deal Finance Plans (DECC, 2015e). Over half of the delivered measures were condensing boilers and solar PV (CCC, 2015b p. 88). Owing to the success of the GDHIF, further funding rounds were anticipated. However, in July 2015, DECC announced that there would be no further GDHIF rounds and funding would cease for the Green Deal Finance Company; effectively signalling the end of the Green Deal (DECC, 2015f).

The 559,742 Green Deal Assessments completed by June 2015 and the success of the GDHIF suggests that consumer appetite for energy efficiency measures does exist but that consumers were unwilling to accept the high interest rates offered under Green Deal Finance Plans. The most recent Government review of DECC's major projects, assigned an Amber/Red rating for their progress on household energy efficiency and emphasised "*the need to shape a cohesive longer-term programme*" (DECC, 2015c). It remains to be seen what will replace the Green Deal. Whatever it is must simultaneously present an attractive deal to millions of home owners and restore confidence in the supply chain.

The Carbon Reduction Commitment

The Carbon Reduction Commitment (CRC) Energy Efficiency Scheme is aimed at improving energy efficiency in large public and private sector organisations responsible for an estimated 10% of UK GHG emissions. Organisations that use over 6000 MWh per annum are compelled to annually report information about their energy supplies and purchase allowances to offset their carbon emissions. These allowances are sold at a fixed price by the Government in two tranches at the start and end of each compliance year. The price of allowances in April 2015 was £16.10/tCO_2.

It has been suggested that the CRC acts as a strong motivator both for construction clients and for large contractors who must report emissions associated with their on-site activities (Davies, Emmitt & Firth, 2013). Although on-site construction emissions represent a small share of whole life carbon emissions, the associated financial burden for contractors in the CRC scheme is significant. Davies et al. (2013) estimated by applying the 2013 allowance price of £12/tCO_2 to on-site construction emissions figures for 2008 that a £6.72 million CRC burden is effectively shared amongst the responsible organisations. Thus the CRC represents a growing financial driver for contractors to measure, benchmark and reduce on-site emissions.

Critics have argued that, although the scheme has motivated better practice within organisations, it is unlikely to have yielded any real emissions savings owing to a failure to consider interactions with the EU ETS. If CRC companies reduce their electricity demand, this allows utilities to sell their EU ETS permits to someone else. Thus, it has been suggested that any emissions savings from CRC participants have probably been emitted by heavy industry elsewhere instead (Carbon Retirement, 2011).

In September 2015 a Government consultation set out proposals to abolish the CRC and move the revenue to a single energy consumption tax based on the Climate Change Levy. The outcome of this consultation was yet to be determined at the time of writing.

Support for microgeneration

The increased use of renewable energy sources at a building level is principally supported by two schemes, Feed-in Tariffs (FiTs) and the Renewable Heat Incentive (RHI). The FiTs scheme, introduced in April 2010, provides a fixed subsidy per unit of electricity generated from microgeneration technologies (such as PV panels and small wind turbines). This acts in addition to the export tariff which pays for excess electricity sold back to the grid. The RHI scheme subsidises participants using renewable energy sources to heat buildings. It started providing payments to non-domestic sector projects in November 2011 and a comparable domestic version was launched in April 2014. Both schemes seek to encourage more use of small scale renewable energy sources in buildings.

The FiTs scheme in particular has been the subject of controversy, owing to the Government's short notice tariff changes in December 2010, which were deemed "*legally flawed*" in a subsequent court case (Vidal, 2011). However, it has proved successful in supporting 3.6 GW of new capacity from nearly 700,000 installations by April 2015, the bulk of these being roof-mounted solar PV (DECC, 2015h). Under the RHI, by May 2015, fewer than 9,000 non-domestic installations (combined capacity 1.5 GW) and 26,000 domestic installations were receiving payments (DECC, 2015g). No estimate of the combined capacity of domestic installations is available; however, some 210 GWh of heat has been paid for under the domestic scheme. This is in contrast to the 3,294 GWh generated under the non-domestic scheme. At the time of writing in July 2015, the Government had just announced a full review of FiTs and a series of minor interim changes (DECC, 2015b).

The popularity of these schemes suggests that there is significant scope for further adoption of microgeneration technologies in both the domestic and non-domestic building stock. However, measures reliant on new low carbon energy sources tend to be a more expensive means of carbon abatement than changes in building fabric, the efficiency of lighting and appliances, and lifestyle measures (CCC, 2008 p. 221). Despite recent reductions in the cost of PV and other technologies, it remains to be seen if subsidising microgeneration installations really represents a cost effective means of mitigating carbon emissions from the built environment.

Minimum Energy Performance Standards

Introduced under the Energy Act 2011, the Minimum Energy Performance Standards (MEPS) are an attempt to accelerate refurbishment rates for energy inefficient buildings. By April 2018, the MEPS will make it unlawful to let properties with an EPC rating lower than an E until qualifying improvements have been carried out. With an estimated 400,000 domestic buildings and 18% of the commercial stock currently rated F or G, the MEPS could motivate dramatic levels of investment in the energy efficiency of existing buildings (DECC, 2015d). The policy also stipulates that from April 2016, landlords will be legally bound to accept tenant requests for cost-effective improvements in F or G rated properties. Whilst the required standard has been set at E level, there is the possibility to increase this in future.

The policy announcement was hailed by the UKGBC as "*the single most significant piece of legislation to affect our existing building stock in a generation*" (Vaughan, 2015). However, the true scope of influence has yet to be proven. The policy was designed to ensure no upfront or net costs to landlords, with improvements expected to be funded through Green Deal finance, ECO funding and local authority grants. With the closure of the Green Deal it may be difficult for many properties to meet this cost-effectiveness requirement through alternative sources of finance. In such instances, landlords are exempted from the standard. There is also the risk of significant embodied carbon being emitted in installation of measures to meet current performance standards in properties that may not remain occupied in the long term. There is no obligation to consider embodied carbon under the scheme.

Landfill tax escalator

The construction sector produces around a third of the UK's total waste, over 13 million tonnes of which ends up in landfill each year in England alone (WRAP, 2011b). In an effort to minimise this waste, the tax on waste to landfill was introduced in October 1996 at a rate of £7/t for active waste and £2/t for inactive waste. The rate started increasing from 1999 as part of a Landfill Tax Escalator. The current rate is £82.60/t for active waste and £2.60/t for inactive waste, with both set to increase further in 2016. These levers are likely to be strengthened going forwards, as the UK is obliged to meet an EC directive that requires at least 70% re-use, recycling or recovery of non-hazardous construction and demolition waste by 2020 (EC, 2008). As price of disposal increases, many alternative options, such as re-use and recycling will become financially preferable. This can potentially reduce embodied carbon by displacing virgin materials production, depending on the energy used in reprocessing the waste materials.

2.3.1.3 Local authority and devolved administration requirements

A number of local authorities have started to enquire about the embodied carbon footprints of developments and introduced reporting requirements as part of the planning process. These include Westminster City Council, Brighton and Hove County Council, Dundee County Council, Leeds City Council, Oxford City Council, Hammersmith and Fulham Council, Camden, City of London, London Borough of Wandsworth, Eastleigh County Council and Huntingdonshire District Council. In response to this trend, the UKGBC has suggested that embodied carbon evaluation may "*increasingly be a differentiator in the planning process*" (UKGBC, 2015e). With the current lack of political support at Westminster for additional regulation of the construction sector, further requirements from local authorities may be a key driver of carbon assessment and abatement in the short term.

There are also indications of increasingly disparate ambitions between Westminster and the UK's devolved administrations. This is typified by the Scottish Government's announcement in June 2015, that the energy efficiency of buildings will be designated a national infrastructure priority (The Scottish Government, 2015). The Scottish Government, at the time of writing, have also yet to provide a statement affirming or retracting their support for implementation of the Zero Carbon Homes agenda. However, the Greater London Authority has intimated that they wish to continue with implementation of Zero Carbon Homes, regardless of national policy. There remains a strong possibility that differential standards relating to carbon reduction will be adopted across the UK's constituent countries and regions.

2.3.2 Voluntary initiatives promoting carbon reduction

In addition to the policies summarised in the preceding section, a number of voluntary schemes promote practice that goes beyond minimum requirements. Clients are increasingly requiring rating against environmental assessment methods, such as BREEAM and CEEQUAL, as a simple means of demonstrating their environmental credentials. This has become so commonplace that such systems are seen as "*quasi-compulsory*" (Fuerst & McAllister, 2011) and serve as "*de facto green building standards*" (Kibert, 2007). In addition to this, CSR concerns have led to a rise in the number of construction companies signing up to voluntary agreements aimed at tackling specific environmental issues. This section summarises the most prominent of these non-regulatory schemes.

BREEAM

The Building Research Establishment Environmental Assessment Method (BREEAM) is a sustainability standard and rating system for buildings. Launched in 1990 as a checklist for rating the performance of office designs in the UK, BREEAM has since expanded into a detailed, globally recognised scheme used in 50 countries on over 250,000 buildings (BRE, 2013a). The scheme now covers a wide variety of new build, in use and refurbishment projects. BREEAM ratings are based upon a third party assessment and verification scheme run by a selection of national scheme operators. Levels are awarded based on a scoring system that combines minimum standards with tradable and innovation credits. Credits are awarded for measures adopted in 9 categories: energy, water, materials, transport, waste, pollution, health & well-being, management and land use & ecology. Environmental weightings are applied to the credits to establish an overall score. This overall score will result in an award of Pass, Good, Very Good, Excellent or Outstanding.

Since its inception BREEAM has steadily grown in popularity and is now the dominant environmental assessment method in the UK. An entire sub industry has emerged to ensure BREEAM compliance and to facilitate the assessment process. The BREEAM Technical Manual has grown from 19 to 406 pages, whilst The Green Guide to Specification (first published in 1996 with basic guidance and a handful of product specifications) has grown to cover over 2000 specifications in its online form (BRE, 2015). Both documents have reached the status of design bibles. BREEAM ratings have been necessary for all public projects since 2006, and are undertaken on many large commercial developments. Whilst this has undoubtedly resulted in an increased emphasis on sustainable design, the scheme is not without criticism.

Typical concerns include the encouragement of a tick-box or credit-chasing approach to design; the incorporation of features that will never be used in order to gain credits; a focus on design calculations rather than in use performance; and a lack of priority amongst the range of environmental concerns. These concerns have led to accusations that BREEAM, and other environmental assessment methods (such as LEED and CASBEE), seek to "*minimise unsustainability*" rather than promote holistic sustainable design (Pope et al., 2004). Indeed, Cole (2005) has argued that environmental assessment methods have come to be seen as an end in themselves. In many cases, the emphasis is on achieving sufficient points for a target rating in the most cost-effective, and not necessarily most sustainable, manner (Hes, 2007). For instance, a recent BREEAM survey found that 48% of professionals in the supply chain thought that projects 'frequently' or 'always' targeted credits that did not add value to the project as a whole (Parker, 2012 p. 20). It has also been demonstrated that the energy and emissions savings the scheme rewards at the design stage are often not realised in practice (Bordass et al., 2004).

The most recent revision of BREEAM, introduced in 2014, featured an increased focus upon materials and a number of new credits. The relative significance of materials increased from 12.5% to 13.5% of the total project score, whilst waste also increased from 7.5% to 8.5%. The new Mat 06 Material Efficiency credit was introduced, as was an opportunity to gain 2 innovation credits for modelling the environmental impact of the building using an IMPACT compliant software tool. Reducing life cycle impacts through green product selection can now yield up to 6 credits in exemplary cases. At the launch of the new version at Ecobuild 2014 it was intimated that further credits for materials would be introduced in future versions as embodied carbon becomes a more prominent concern. However, in spite of these positive recent changes, material life cycle impacts remain a fairly minor component of the overall score. There are no minimum requirements for life cycle impacts to achieve any of the overall ratings and, in the majority of projects, material life cycle impacts will contribute less than 5% to the total score. There are much easier means for designers to achieve equivalent credits. For example, provision of cycle storage and 'cyclist facilities' (i.e. a shower and somewhere to change) achieves 3 transport credits. Factors related to the site location, which is likely already determined, also affect the score significantly more than any material choices. In short, whilst the life cycle impacts of materials are of growing significance in BREEAM, the scheme still provides little incentive to reduce them.

CEEQUAL

CEEQUAL is an evidence-based sustainability assessment, rating and awards scheme for civil engineering, infrastructure, landscaping and public realm projects (CEEQUAL Ltd., 2013). Originally developed by an industry consortium led by the

Institute of Civil Engineers, CEEQUAL was launched in 2003. Now in its fifth version, by the start of 2015 it had issued 260 final and nearly 100 interim Awards, with a further 250 projects under assessment (CEEQUAL Ltd., 2015). The assessment is based upon eight mandatory and one optional topic: project strategy (optional); project management; people and communities; land use and landscape; historic environment; ecology and biodiversity; water environment; physical resources; and transport. Based upon evidence provided, CEEQUAL trained assessors score the project against set questions for each area. Scores are then summated. This process is then externally verified. The scheme ultimately awards overall grades of Pass, Good, Very Good and Excellent. It is, in essence, an equivalent of BREEAM focussed on civil engineering works. Unlike BREEAM, CEEQUAL provides a heavier incentive for life cycle assessment and resource efficiency. For example, Section 8.2 includes up to 56 points for conducting a full project LCA and a further 56 points available for demonstrated reductions in environmental impacts. However, in November 2015 BRE announced the acquisition of CEEQUAL business operations and the intended merger of the schemes in 2017. It remains to be seen how this will affect the scoring priorities and frequency of use.

Halving Waste to Landfill Commitment

Between 2008 and 2012 WRAP administered a scheme intended to drastically reduce construction waste to landfill. The scheme was expected to encourage the increased use of recycled and recovered material, which could in turn reduce emissions by displacing virgin material production. 602 organisations, covering a considerable proportion of the industry, signed up to a commitment that stated they would "*work to adopt and implement standards for good practice in reducing waste, recycling more, and increasing the use of recycled and recovered materials*" (WRAP, 2011b). WRAP subsequently declared the project as "*a great success*" owing to the stimulation of client interest, dissemination of best practice and the widespread use of WRAP's procurement wording (WRAP, 2013c). The scheme was undoubtedly influential; however, it is important to ask not only if the scheme had the desired effect on attitudes but whether it achieved the headline goal of halving waste to landfill.

At the start of the scheme construction firms were responsible for generating over 100 million tonnes of construction, demolition and excavation waste each year. It was estimated that a 28% cut was achieved in the first year of the scheme alone (2008-2009); a result which was trumpeted by WRAP's chief executive as an indication the sector was "*well on track to deliver the target by 2012*" (Environment Media Group Ltd, 2011). However, this was reversed by a 27% increase in 2009-2010 (Hobbs, 2012). Effectively a 2% overall reduction had been achieved by 2010 relative to the 2008 baseline. Statistics for 2012, which were due to be published in June

2013, have yet to surface, and it appears unlikely that they ever will. Following a 2013 funding review, WRAP's funding was cut and their work in the construction sector largely ceased. The combined effects of the recession and the scrapping of Site Waste Management Plans saw a simultaneous decline in interest in waste from some parts of the industry. Whilst some of the firms that reported data under the scheme may well have achieved the target, there is no public evidence to suggest that the target was achieved in aggregate across the scheme participants.

Critics of the scheme argued that "*much of the diversion from landfill currently reported is achieved either through incineration and the recovery of energy, or ultimately through the transport of the materials to be processed in faraway places such as China*" (Kinsey, 2013). This could potentially undermine the carbon benefits anticipated from greater re-use and recycling. Indeed, whilst "*many clients now specify diversion from landfill targets, it's still unusual to see targets specifically for reuse, which is higher up the waste hierarchy*" (Kinsey, 2013). Thus, whilst the scheme was undoubtedly successful in raising interest and encouraging greater specification of recycled materials it did little to encourage material re-use, suffered from a significant loss of momentum over time, and its core message was only taken to heart by a small portion of the industry.

Built Environment Commitment

In July 2014, the Halving Waste to Landfill commitment was in part replaced by a new Built Environment Commitment. The new commitment was initially developed by WRAP and subsequently taken forward by BIS and the GCB after the aforementioned funding cuts. The Built Environment Commitment is essentially a public statement of intent to take action that contributes to a low carbon, resource efficient built environment. The precise wording is tailored to each organisation. At the time of writing 13 Commitments had been published, the most high profile of which was signed by 30 members of the UK Contractors Group (UKCG, 2014). The UKCG commitment included pledges to:

» Reduce direct emissions from onsite construction and related activities, with an aim to take at least 0.5 $MtCO_2e$ out of our processes by 2025 and to contribute to wider measurable reductions in capital carbon.
» Halve construction waste production by 2020, relative to turnover, compared to 2010.
» Continue work to reduce the amount of waste sent to landfill, and have set collective targets for 2020.
» Continue to implement agreed member protocol giving "*preference to procuring products which are able to demonstrate compliance with a recognised responsible sourcing scheme*", and supplementary commitment on sustainable timber procurement.

- » Report use of water (potable water through the mains plus abstracted and tankered water), and continue to take steps to promote effective water management, including use of alternative approaches that negate need for use of potable water in construction.
- » More widely, UKCG will promote the concept of the 'circular economy' and greater efficiency in the use of resources and materials over the product lifecycle.

It is deeply encouraging to see a specific commitment to embodied emissions reduction from such a major industry group; however, this is essentially a restatement of the 2012 on-site emissions targets from the Strategy for Sustainable Construction which were comprehensively missed (Construction Manager, 2014). Whilst it remains to be seen if the targets will be met this time, the Commitment does constitute a clear statement of ambition from the largest UK contractors. It is hoped that further firms and collectives will launch commitments featuring similar ambitions.

2.3.3 International developments

In spite of the current lack of national drivers for embodied carbon reduction, there are a growing collection of international precedents. In 2013 the Dutch government introduced embodied carbon reporting requirements for residential and office developments over 100 m^2. Singapore intends to introduce comparable requirements in the next year. The German government have also required whole life carbon assessments on all publicly funded projects since 2008. The Dutch, French and Germans now maintain national databases of embodied carbon factors for building products that are widely used in assessments. The Swiss have also developed a widely used voluntary standard for assessment. The Belgians and French have introduced regulations requiring EPDs to support the environmental claims of product manufacturers. Several international environmental assessment schemes, such as Green Star (Australia), LEED (U.S.) and DGNB (Germany), have also recently introduced additional rewards for the assessment of full lifecycle impacts.

The EC is taking an increased interest in embodied carbon and resource efficiency. In July 2014 the EC issued a communication covering perceived resource efficiency opportunities in the construction sector (EC, 2014). The communication was principally concerned with two topics: establishing a common European approach for assessing the environmental performance of buildings; and improving the market for recycled construction materials. The proposed framework is intended to provide a common set of clearly defined and measurable indicators for environmental performance. The ten measurable elements initially proposed in the communication are:

- » Total energy use, including operational energy and embodied energy of products and construction processes

- Material use and the embodied environmental impacts
- Durability of construction products
- Design for deconstruction
- Management of construction as well as demolition waste
- Recycled content in construction materials
- Recyclability and reusability of construction materials and products
- Water used by buildings
- The use intensity of buildings
- Indoor comfort

The framework is intended to generate more comparable performance information throughout the region for consumers and policy makers, and standardise assessment practice across European construction firms. In the long term, the intention is that these metrics will be used in target setting and may be incorporated into legislation. The framework is intended to be broad and should work alongside or in isolation from existing sustainability assessment methods such as BREEAM and LEED.

The EC is currently engaging with a wide range of stakeholders to select an appropriate set of indicators and metrics. This is principally being coordinated by the Europe Regional Network of the WGBC; who are running a series of workshops in partnership with Green Building Councils across Europe (UKGBC, 2014b). This consultation is set to continue into 2016. Should embodied impacts be included in these common metrics, it could motivate a significant expansion in the practice of whole life carbon assessment. Similarly, as UK firms face increasing requests for embodied carbon assessment on overseas projects, they are more likely to implement similar procedures on domestic projects.

2.3.4 Discussion of regulation and voluntary drivers

Over the past decade policy makers have responded to strategic national carbon reduction targets with a suite of policies that encourage carbon reduction in the built environment. In the early part of the 21st century both European and UK policy makers largely equated carbon emissions with day-to-day energy consumption. This dominant interpretation resulted in policies focussed on reducing operational energy use through improvements in building fabric and the uptake of low carbon technologies, such as heat pumps. The age of the UK's building stock also required a particular focus on retrofit measures. These policies were supplemented by generous financial incentives for the installation of microgeneration technologies. This selective interpretation of carbon reduction as reductions in regulated energy use has severely restricted the range of carbon mitigation solutions pursued by the industry. This focus on operational emissions came despite warnings, such as those by Ibn-Mohammed et al. (2013) that "*by omitting embodied emissions in the building sector, policy developments related to energy and emissions are in effect neglecting the bigger picture and truncating the* *wider benefits that can be derived from a more holistic policy framework*". Only recently have there been initial signs of movement towards a broader interpretation.

The high profile Low Carbon Routemap for the Built Environment and Infrastructure Carbon Review both stressed the need to address embodied emissions and there is evidence of mounting support amongst industry practitioners and at a local authority level. In spite of this, embodied carbon has not yet become part of mainstream building policy developments, and no national regulation promotes embodied carbon assessment or reduction. National drivers remain limited to a small number of voluntary initiatives and environmental assessment schemes. Where embodied carbon is considered in such schemes, it represents a small, and often isolated, component of a larger appraisal framework incorporating a wide range of environmental factors.

Even in the case of operational emissions, where headline targets for regulation have been forthcoming, much of the policy detail has been subject to repeated revision and sudden removal. It is clear that hesitancy and mixed messages from policy makers has undermined industry confidence, delayed investment and stifled ambition. This is unsurprising as research has repeatedly shown that clear, structured and timely legislation in this sector is essential, as where regulatory obligations do not exist, sustainability objectives are often ignored (Williams & Dair, 2007). Indeed, the CCC emphasised in their most recent progress report to Parliament that the numerous policy changes seen over the past few years have substantially affected the delivery of measures and eroded confidence in the supply chain (CCC, 2015b p. 89).

The need for greater clarity and consistency has been a recurring theme throughout industry reports and consultation responses over the past decade. For instance, when considering the implementation of the Zero Carbon agenda in 2007 the Calcutt Review warned that "*to be effective, Government intervention must be credible, clear and sustained…if there is any uncertainty about the Government's commitment, either to the target or to the timetable, the flow of investment will rapidly dry up.*" (Calcutt, 2007 p. 89). Nine years on it is obvious that none of these three criteria were met. The credibility of this flagship policy was repeatedly undermined by ambiguous statements from Government ministers. The definition of zero carbon was changed multiple times despite constant appeals for clarity. Interim steps on the timetable were repeatedly missed, delayed or watered down – including crucial changes to Part L – and ultimately the policy was withdrawn without consultation. In short, the policy intervention was not credible, clear or sustained. In retrospect the Calcutt Review was also remarkably prescient in predicting "*the practical consequence of a laissez-faire approach to development in the market will be that the housebuilding and construction products industries and renewable energy providers are not ready to deliver zero carbon by 2016. This will become apparent well before that date* *is reached, and Government will have to choose whether to prefer high-cost zero carbon and a shortfall against housebuilding targets, or a difficult retreat from 2016"* (Calcutt, 2007 p. 95). The response to Zero Carbon was largely left to a fragmented and highly competitive market in which a number of the major actors were never committed to the agenda. Many firms within the industry lacked confidence in the technologies, the skills to install them, and did not have confidence that legislation would ultimately be implemented (Osmani & O'Reilly, 2009). Financial concerns were exacerbated by the recession, and ultimately, as predicted, the Government prioritised housebuilding targets and retreated from the Zero Carbon ambitions.

Meanwhile, the principal policy promoting retrofit, the Green Deal, was nothing short of a monumental failure. Intended to encourage unsubsidised retrofit of 14 million properties, it supported less than 30,000, the majority of which received substantial public subsidy through the GDHIF. The failure, and predictable closure of the scheme, combined with the removal of the Code for Sustainable Homes and Zero Carbon targets have left a policy vacuum that threatens to undermine the 50% carbon reduction target set out in Construction 2025. Prior to these policy announcements, the CCC estimated a policy gap in addressing emissions from buildings of 16 $MtCO_2$ by 2025 (CCC, 2015b). With the gap now likely to exceed 20 $MtCO_2$, there is an urgent need for a reappraisal of long term policy options. The inclusion of embodied carbon within a renewed scope, offers the opportunity to close this growing policy gap.

Examples of how adopting a broader scope can be effective in driving carbon reduction can already be observed in heavily regulated sectors of infrastructure provision, such as the water industry. In 2009 Ofwat introduced reporting requirements for embodied carbon associated with proposed capital investments into their 5-yearly price review process for water and sewerage companies. Firms responded by developing large libraries of asset and component level embodied carbon data, in-house modelling and decision-making tools. This approach, though not without challenges, has been successful in encouraging carbon assessment and mitigation throughout the water industry (Keil et al., 2013). It is unclear whether regulation would provoke a similar response amongst the more diverse and fragmented buildings segment of the industry. Small design firms are less likely to have the capacity for such developments and would likely require provision of supporting tools and LCA databases were requirements to be introduced. Such supporting tools are discussed further in Section 2.4.

2.3.5 Client requirements

According to the ICE: "*the role and performance of clients is the single most important factor in determining the success of construction projects*" (ICE, 2009). Clients with a clear and ambitious project vision and the ability to communicate it to the project team largely drive best practice in the construction industry. The importance of the client in providing effective leadership and establishing a productive project culture cannot be underestimated. In the case of embodied carbon, in the absence of regulated requirements, current assessment and mitigation practice is driven solely by clients. This section provides a brief overview of typical requirements from industry leaders and a discussion of the corresponding business case.

There has undoubtedly been a growing global demand for green credentials from clients, as noted in Section 1.4.7. In an influential report on the business case for green building, the WGBC note that "*clients are increasingly aware of sustainability and energy issues and demand more expertise from the industry and the collaborative teams that are brought together to deliver their projects*" (WGBC, 2013). Obvious concerns such as rising energy costs, CRC allowance prices, and the introduction of MEPS is set to strengthen client demand for green buildings. This is reflected in a projected 22.8% annual growth in sustainable and green construction in the next two years (GCB, 2015). Clients are increasingly seeking to differentiate themselves through green credentials both in the marketplace for their products and in the labour marketplace. CSR commitments regularly target the reputational benefits associated with going green, as companies seek to establish a public association with sustainability. Indeed, 'recognition or industry standing' remains the most common reason for the use of green building assessment schemes such as BREEAM (Parker, 2012).

This growth in green has given rise to more frequent carbon assessment and mitigation. Often this is motivated solely by requirements for building assessment schemes; for instance, more than half of local authorities in England have a BREEAM requirement as part of their local development framework, with a greater proportion in urban centres (Parker, 2012). However, an increasing number of clients are supplementing such targets with specific requirements relating to embodied carbon assessment. For instance retailers Marks and Spencer have introduced a specific 2020 ambition for embodied carbon reduction into their Plan A commitments (Marks and Spencer, 2014 p. 28). British Land's extensive sustainability brief for developers includes a requirement to reduce embodied carbon in concrete, steel, rebar, aluminium and glass by 15% compared to the concept design on projects over £50 million (British Land, 2014). Even mass housebuilders such as Barratt Developments have introduced a 2015 performance target seeking to minimise embodied carbon (Barratt Developments PLC, 2014).

Clients are increasingly sharing best practice, and have benefitted from the publication of accessible procurement guides, such as the WRAP 'Client procurement guide for carbon efficient buildings' (WRAP, 2013b). These guides offer basic information for clients and example wording for inclusion in project briefs. Industry events such as the UKGBC Embodied Carbon Week – established as a response to client requests – have provided further opportunities for clients to share experiences and compare requirements (UKGBC, 2014a). A number of major UK clients – such as British Land, Derwent London, Land Securities and Tishman Speyer – have taken a prominent role in promoting the embodied carbon agenda. They have repeatedly challenged the industry to further develop a business case for reducing embodied carbon where carbon reduction is more closely related to cost savings.

Prior to substantial funding cuts, WRAP produced a small body of work summating the current business case for embodied carbon reduction. This included a summary of the Business Case for Managing and Reducing Embodied Carbon in Building Projects (WRAP, 2014b); an information sheet on cutting embodied carbon in construction projects (WRAP, 2011a); and a broader business case for resource efficiency in construction (WRAP, 2013a). WRAP argues that the business case for embodied carbon reduction principally centres on cost savings associated with a reduction in material use. Additional mooted benefits include: establishing a reputation for good environmental management; the possibility of attracting more desirable tenants; greater resilience to energy and material price rises and resource scarcity risks. The future introduction of local or national assessment or reduction requirements also poses a significant regulatory risk. Other studies have also argued there is a potential benefit for early actors as: "*contractors that can demonstrate improvements in their reduction of embodied energy are likely to have a competitive advantage and will also be well positioned to influence industry standards and policy strategy*" (Davies et al., 2014).

The evidence base for cost reductions associated with reduced material use is still developing. Prominent examples from the infrastructure sector of the industry are frequently cited. For example, Anglian Water realised significant savings in capital cost whilst achieving a 54% reduction in embodied carbon emissions between 2010 and 2015 (Anglian Water, 2015). These examples support the core message of the ICR that reducing carbon reduces cost. However, carbon savings of this magnitude have yet to be widely replicated in the less materially intensive building sector at reduced cost. The current rule of thumb amongst experienced practitioners suggests that the first 5-10% embodied carbon reduction should be at least cost neutral but substantial reductions (>30%) may require additional upfront costs. However, amongst the broader industry, the perception of a 'green premium' associated with constructing higher performing, lower carbon buildings is rife. For instance, meeting BREEAM 'Outstanding' is often suggested to cost on average 10-12% more than meeting local building codes (Mann, 2014). By contrast some studies have argued that "*there is no significant difference in average costs for green buildings as compared to non-green buildings*" (Davis Langdon, 2007). Irrespective of the true magnitude of such a premium, a handful of studies have demonstrated a sizeable 'perception gap', whereby construction professionals believe the green premium to be substantially higher than in reality (WGBC, 2013 p. 26). Similar surveys have also demonstrated that industry professionals substantially underestimate the carbon emissions associated with the built environment (Willoughby, 2008). This combination of underestimating the significance of the issue and overestimating the costs of addressing it, undoubtedly leads to reduced action.

The reality is that the magnitude of the premium is probably more dependent upon the project approach. When all stakeholders, cost strategies, program management and environmental strategies are integrated into the development process at an early stage, the cost premium is greatly reduced. Such early engagement can avoid expensive bolt-on strategies and soft costs later in the project such as redesign work. In some instances these upfront costs can also be offset by decreased long-term life cycle costs. However, despite significant industry lip service, there is still little uptake of life cycle costing (LCC) in practice. Matthiessen argues this is due to a lack of understanding of the value and capability of LCC; a distrust in the inherent uncertainty of LCC; and an often irrational response to LCC results (WGBC, 2013 p. 29). There is also an inherent limit to the range of clients for whom an LCC approach is appropriate. Clients who are not occupiers or long term asset holders are unlikely to be swayed by potential returns later in the life cycle unless they translate into an increased sale price. Limited evidence of mooted premiums in asset value for green buildings has been found and studies have speculated that these premiums will diminish over time as prime and green converge (RICS, 2010; Fuerst & McAllister, 2011; Stevens, 2013; Chegut et al., 2013; Fuerst et al., 2015).

Recent studies have also suggested that the growing prevalence of short-term UK real estate investors providing tenants with short term leases (<5 years) is substantially reducing investment timeframes (Elliott et al., 2015). The recession has also restricted access to capital, increased concerns about marginal up-front costs and resulted in the worst downturn in construction activity since WWII (Elliott et al., 2015; ONS, 2013b). Private commercial output reduced by a third between 2008 and 2012, whilst housebuilding reached the lowest peacetime levels since 1923 (CBI, 2012). Construction sported the highest redundancy rates of any sector throughout the recession, with a peak drop in employment of 428,000 workers – roughly 17% of the total workforce (UKCG, 2012). This significant loss of employees yielded a loss in skills that the industry is still recovering from. The severe weakening of construction company finances gave rise to the realistic attitude that "*sustainability is no longer as important as making a profit*" (Osmani & Gordon, 2012). Total industry output remains below pre-recession levels at the time of writing at the end of Q2 2015 (ONS, 2015b). As does the industry attitude summarised by Laing O'Rourke's Head of Sustainability and Carbon Management at Ecobuild 2015: "*it's all about cheaper and faster since the recession*". In such an economic climate, even the most marginal increases in upfront cost are unpalatable for many investors and developers.

With design and construction of a commercial building typically amounting to only 10% of the total lifecycle costs, attempts to revitalise the business case for green building in the wake of the recession have focussed upon the evolution of a more holistic business case targeting improvements in workplace productivity and the health and wellbeing of occupants. This trend has been spearheaded by successive WGBC reports (WGBC, 2013; WGBC, 2014a) and the prominent 'Better Places for People' campaign (WGBC, 2015). The UKGBC is a proactive member of this campaign and is leading two ongoing task groups investigating impacts in retail and residential properties. This campaign has many followers within the UK industry, who are now pursuing a health and wellbeing agenda within their portfolios. At Ecobuild 2015, Chris Brown, CEO of Igloo Regeneration, went so far as to claim that "*health and wellbeing is the new climate change*" in terms of building design and development. This comment reflects an oft observed fickleness within an industry that progresses through fleeting trends. In such an environment, subject to competing narratives and lacking robust data on the costs and benefits of low carbon building, it can be difficult for clients to determine priorities and establish requirements. In spite of this, several high profile clients have expressed a willingness to take a lead on embodied carbon. Ultimately their experiences will resolve the debate around cost premiums and develop the nascent business case. In the long term it is likely that the strength of this business case will determine the speed of carbon reduction in the built environment.

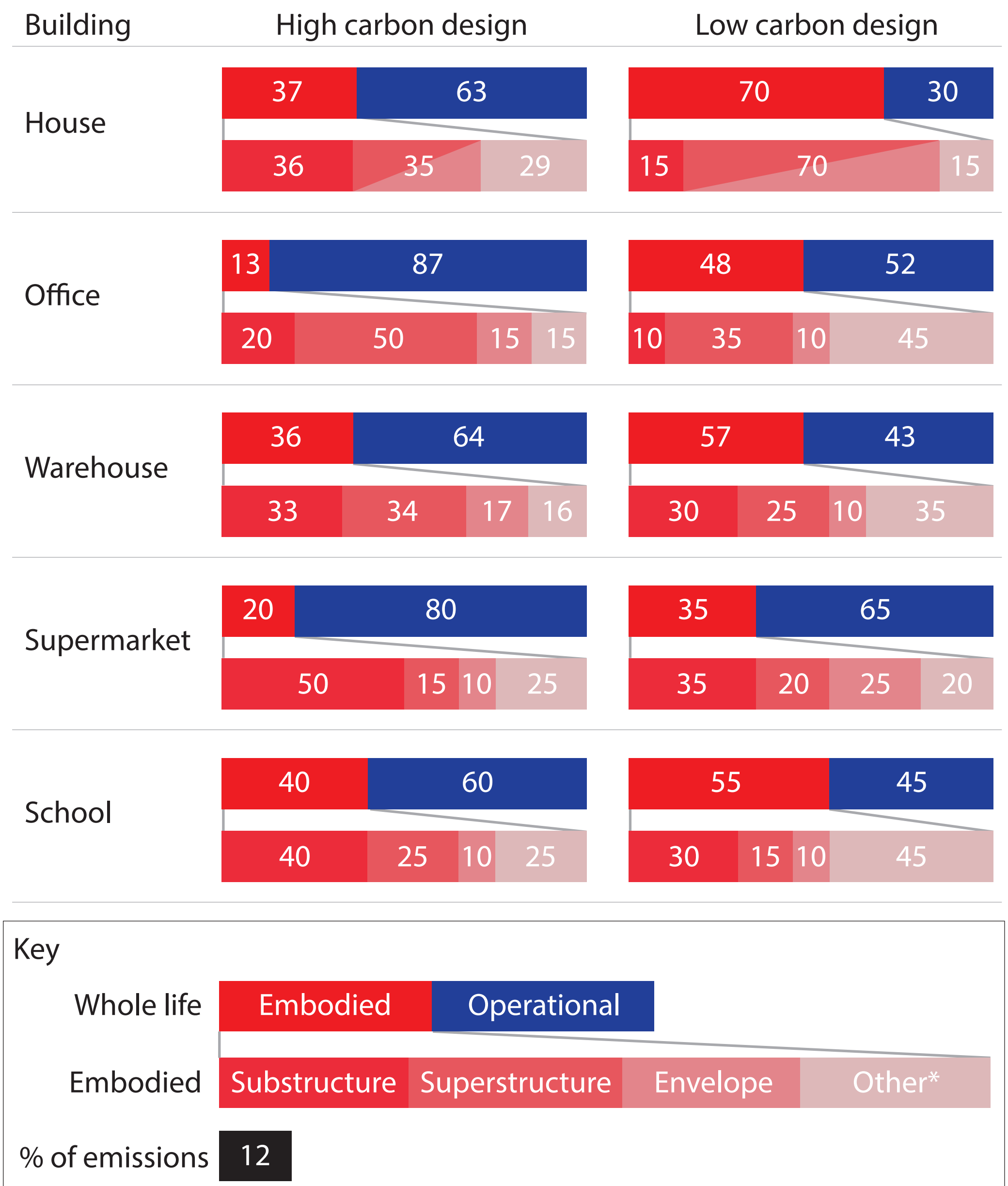
2.4 Current carbon assessment and mitigation practice

2.4.1 Embodied carbon assessment at the project level

Embodied carbon assessment has been undertaken on demonstration and publicly funded projects for some time; however, it was not until 2007 that it reached the interest of commercial developers. The first commercial company to address this issue, Prologis, measured and offset 110% of the embodied carbon associated with the development of their distribution centre in Pineham; and standardised this approach across all UK projects from 2009. Their example has been followed by other large private sector clients – such as British Land, Land Securities and Marks & Spencer – who now require an assessment of embodied carbon on all high value projects. The majority of these clients are involved in office, retail or warehouse developments, with few housebuilders active in embodied carbon assessment. Similar variations are observed in the infrastructure segment of the industry, where embodied carbon assessment is required by regulators in certain sectors such as water and sewerage, common in other areas such as road and rail development, and rarely, if ever, considered in sectors such as telecommunications.

The precise embodied carbon intensity and distribution of emissions will vary from project to project dependent upon the particular design characteristics, building materials, carbon assessment boundaries and numerous other factors. Some example proportions of whole life carbon emissions for different building types are displayed in Figure 4. These should be viewed as illustrative only, as there is no such thing as a 'typical' building and individual projects cannot be taken as representative of most projects within a given category. The impact of certain elements, such as foundations, are also highly dependent upon site conditions. The proportions for infrastructure projects exhibit even greater variance, and are best viewed in parallel with carbon impacts incurred from changes to user behaviour. For instance, phases

Figure 4: Example whole life carbon emissions breakdowns



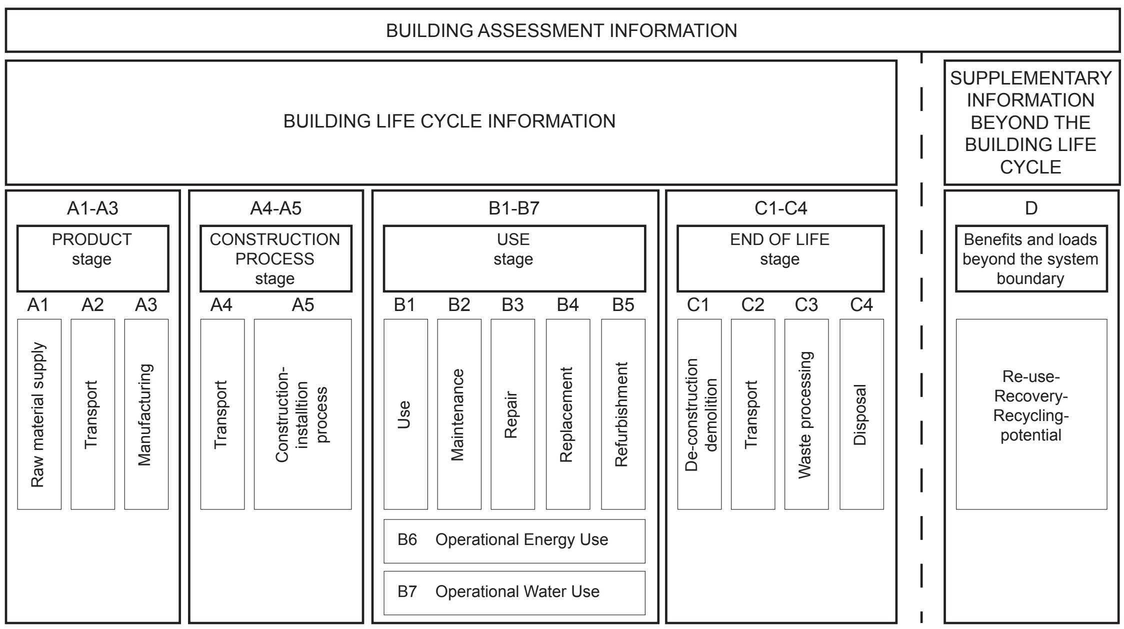
* 'Other' includes elements such as M&E, lifts, internal fit out, external works and so forth.
Note: all figures are indicative and consider only embodied emissions incurred to practical completion. Figures are based upon assessments reported in (Arup, 2014; Clark, 2013; Din & Brotas, 2016; Gavotsis & Moncaster, 2015; Kelly et al., 2012; NHBC Foundation, 2012; Rai et al., 2011; Roberts & Li, 2012; Sansom & Pope, 2012; WRAP & UKGBC, 2014)

one and two of HS2 are expected to incur up to 13.3 $MtCO_2$ of emissions in their initial construction, but save comparable emissions from passenger modal shift and released freight capacity (Temple-ERM, 2013).

Assessment of embodied carbon at the project level can be conducted at different stages of the project development. Best practice is to track embodied carbon throughout the project from an initial design phase estimate through procurement and construction to a final assessment upon project completion. For a practical example of this see the publicly available embodied carbon tracking report from British Land's 5 Broadgate development (Arup, 2014). Whilst this represents best practice, in most cases where embodied carbon is assessed by the UK industry it tends to be only after the building has been constructed (Moncaster & Symons, 2013). The system boundaries, means of calculation and data sources for the assessment vary widely between practitioners. The variations in these three elements are considered in the following paragraphs.

Academic studies differ widely in their system boundaries, as indicated in a review of 25 prominent LCA studies by Davies et al. (2014). This is in spite of the introduction of a common standard for assessment, BS EN 15978, in 2011. The life cycle stages considered within the standard are shown in Figure 5. Whilst some academics, and a limited number of experienced practitioners, adopt broad cradle-to-cradle system boundaries, the majority of the industry is less well-informed and typically adopt cradle-to-gate (A1-A3), cradle-to-site (A1-A4) or cradle-to-practical completion (A1-A5) assessments (Gavotsis & Moncaster, 2015), as advocated by prominent industry publications (RICS, 2012). A typical cradle-to-practical completion assessment involves assembling an inventory of all the materials, fuel

Figure 5: Life cycle stages from BS EN15978:2011Sustainability of construction works - assessment of environmental performance of buildings - calculation method



and electricity used to produce the building. The quantities of fuel and electricity are then multiplied by standard carbon factors per unit, such as those suggested by DEFRA (2012). Meanwhile comparable embodied carbon factors are applied to the consumption of each material or building product. By this means the total embodied emissions can be enumerated.

Most practitioners are conducting such calculations using simplistic in-house carbon assessment tools, often comprised of a series of interlinked Excel spreadsheets compiled by a single practitioner. These often lack sufficient documentation to be adopted by others, are ineffective at dealing with variations in design, and require regular updating of the background data (Ariyaratne & Moncaster, 2014). In a minority of cases material emission factors are being integrated into Building Information Models (BIM), allowing for immediate assessment of carbon and cost impacts throughout the design phase. This approach allows automation of calculations and greater flexibility, with BIM's ability to simultaneously host graphical, quantitative and qualitative data. This is achieved through plug-ins such as BRE's IMPACT (Doran, 2013), Butterfly (BLP Insurance, 2013), Tally (KT Innovations, 2014) and Rapiere (Rapiere, 2015). The integration of LCA data into BIM represents a tremendous opportunity to improve estimation and mitigation of embodied carbon at the design stage. A recent industry survey and series of interviews suggested there is strong support for this approach (Ariyaratne & Moncaster, 2014). However, in spite of incentives, such as the offer of BREEAM innovation credits, there has been little uptake to date of the available tools.

In practice, assembling such basic data as the volume of fuel consumed in transport or the volume of materials sent to site can prove challenging, as it involves close documentation of every site delivery. Problems are frequently noted with the lack of a standard method for the collection of data on the type, number and specification of components used, their transport to site, the construction energy used, the waste produced and its destination (Davies, Emmitt & Firth, 2013; Gavotsis & Moncaster, 2015). Many contractors are not yet familiar with the concept of embodied carbon, let alone detailed reporting. Even within leading companies significant discrepancies can still be observed between the knowledge and attitudes of director-level and project-level operatives (Davies, Emmitt & Firth, 2013). Consequently, even in best practice examples such as 5 Broadgate, certain inconsistencies can be observed in the data (see Figure 6 overleaf for example). This problem is compounded in instances where multiple sub-contractors are used for different construction packages, each of whom has responsibility for procurement of materials (Sahagun & Moncaster, 2012; Davies, Emmitt & Firth, 2013).

Gavotsis and Moncaster (2015) provide a good summary of the typical issues faced during the process of estimating embodied carbon through a case study on a Cambridge school building. Despite "*collaboration and keen interest*" from "*well-*

informed" parties data collection proved challenging. The speed and quality of data collection was hampered by the fact that the main contractor had employed several different subcontractors for different packages - as is normal practice - which led to an estimated 10-30% missing data. Data for a number of components were either "*not identified at all; identified but out of scope; identified but not calculated because of their size or complexity; identified but not calculated due to the lack of information; or identified but only a rough estimate of impact made*". Difficulties were also encountered in gathering data on the composition of on-site and off-site waste. Yet, despite these substantial omissions, and the failure to account for future decarbonisation of the electricity grid, embodied carbon still accounted for 41% of total life cycle emissions. This clearly demonstrates the significance of embodied impacts in structures of this type. The authors also noted the significance of the boundaries set for assessment, arguing that if only A1-A3 cradle-to-gate impacts had been considered, the embodied impacts would have been underestimated by approximately 50%. Similarly, they emphasised the importance of gathering data for materials actually received on site rather than depending solely upon design documents. If the calculation had been based only on the Bill of Quantities then embodied carbon would have been underestimated by 25%. Similar problems with sub-contractor information, data capture and ambiguity were noted by Davies et al. (2013b) when appraising a large contractor's assessment of a UK warehouse project. Comparable shortcomings in data management procedures were also observed across a further 24 healthcare and education projects (Davies, Emmitt & Firth, 2013).

Owing to the difficulty of assembling data for all materials and products, some practitioners are choosing to focus on 'carbon-hotspots', corresponding to a subset of key building elements or materials (UKGBC, 2015d). Indeed a group of industry practitioners, referring to themselves as the Embodied Carbon Task Force, recently advocated a consistent set of minimum boundaries for assessment, indicated in

Figure 6: Four tonnes of unspecified concrete for who knows what - a typical problem encountered gathering data on site (Arup, 2014)

	Calculation 2 (gate to site)					
	Mix Design (Buro Hapold Ref)	**Delivery ref (mode of transport)**	**Total material weight delivered to site (kg)**	**Distance materials travelled to site (km)**	**Carbon factor (kgCO2e /m3.mile)**	**Carbon (kgCO$_2$**
Skanska	LCMD	*concrete truck*	418,570.00	8.00		
Skanska	Male hard piles	*concrete truck*	555,180.00	8.00		
Skanska	Female hard piles	*concrete truck*	62,020.00	8.00		
Skanska	female firm piles	*concrete truck*	256,760.00	8.00		
Skanska	micro piles	*concrete truck*	131,340.00	8.00		
Skanska	who knows	*concrete truck*	4,180.00	8.00		
Skanska	guide wall	*concrete truck*	1,710.00	8.00		
Byrne Bros	In Situ Concrete	*concrete truck*	106,324,080.00	9.66	0.35	
	Total carbon footprint (delivery to site)					

Figure 7. The adoption of a hot-spot or minimum boundaries approach could make the assessment process appear less onerous and encourage more widespread assessment; however, the exclusion of certain elements and life cycle stages can, in certain cases, result in significant underestimates of embodied carbon. For example, the carbon emissions occurred in maintenance, repair and replacement of components (B2-B4) throughout the building's operation are typically excluded from assessments. This can account for a substantial share of total embodied carbon emissions for buildings with frequent refurbishment or replacement cycles, such as commercial offices. For example, maintenance accounted for 39% of total life cycle embodied carbon on British Land's Ropemaker Place development (dcarbon8, 2009).

A further factor frequently responsible for downplaying the significance of embodied carbon is excessive assumptions of building service life. For instance, a study by Richardson et al. (2014) compared the assumed service lives of 6 Sainsbury's supermarkets subject to carbon assessments with data on recent store demolitions. Whilst the carbon footprint of a store was typically assessed over an assumed service life of 30-60 years, the mean age of stores subject to demolition was observed to be only 23 years. The authors argued that this was typical of a broader practice of making unjustified assumptions about service life in building LCAs, with service life usually assumed to be equivalent to the design life required under local building codes. This does not reflect the reality that the nominal design life bears no connection to the actual service life of a building. Whilst the authors advocate the use of parametric techniques to account for unpredictable service lives, this approach is rarely adopted in practice. The absence of a consistent approach on this and other

Figure 7: Embodied Carbon Task Force suggested common boundaries for embodied carbon assessment (Battle, 2014)

Stage	Sub Stage	Item	Commercial		Residential	
			Minimum	Optional	Minimum	Optional
Product Stage	A1	Raw Materials	X		X	
	A2	Transportation	X		X	
	A3	Manufacture	X		X	
Construction Process	A4	Transportation	X		X	
	A5	Construction and Installation	X		X	
Use Stage	B1	Use	N.A		N.A	
	B2	Maintenance		X		X
	B3	Repair		X		X
	B4	Replacement		X		X
End of Life	C1	Deconstruction and Demolition		X		X
	C2	Transportation		X		X
	C3	Waste processing		X		X
	C4	Disposal		X		X
Re-use	D1	Re-use		X		X

issues frequently precludes direct comparison of buildings and leads to common criticisms. For example, Ibn-Mohammed et al. (2013) argue that "*published results of embodied emissions are laced with inconsistency and most times are not comparable due to differences in calculation procedures, age of data and a host of other factors*".

Whilst the most prominent industry methodology, published by the RICS (2012), advocates more narrow system boundaries, some academic authors have argued for substantially broader boundaries incorporating aspects such as human and capital energy inputs and dependence upon local infrastructure (Dixit et al., 2013). Undoubtedly there is a balance to be struck between these extremes. Resolution of this problem requires adoption of a detailed standard approach, framed within EN 15978, that balances the need for rigour and comprehensive coverage with practical considerations. Such a standard should be developed through a participatory approach with a broad group of stakeholders, led by an impartial and respected industry institution with authority and experience developing standards. The interest generated by the RICS methodology clearly demonstrates the industry desire for standardisation, but as embodied carbon assessment skills improve, there is clearly a need to revisit the initial RICS approach.

Aside from these concerns, industry practice is improving, with the recent dissemination of numerous pieces of guidance for designers (Clark, 2013a; UKGBC, 2015d) and clients (UKGBC, 2015e). 2014 saw the UKGBC host an inaugural Embodied Carbon Week, featuring numerous events and participants from 300 organisations (UKGBC, 2014a). The popularity of this series of events reflected the status of embodied carbon as a rapidly growing priority within the UK industry. The week also featured the launch of the public WRAP Embodied Carbon Database, which allows users to share and compare their project level embodied carbon assessments (WRAP & UKGBC, 2014). At the time of writing the database featured assessments for some 233 projects and is set to expand substantially with an impending transfer of database ownership to the RICS. The database facilitates relative benchmarking of projects, albeit from an initially small sample size. It is hoped that this will aid both designers and clients, and a number of companies have committed to add all future project results to the database (Battle, 2014). However, as embodied carbon assessment becomes more commonplace, it is important to question the underlying product embodied carbon factors upon which it depends.

The embodied carbon factors for building products can come from a variety of sources of differing quality. Indeed, the collection, assessment and maintenance of accurate and transparent product data is one of the key hurdles to the assessment of embodied carbon in buildings (Moncaster & Symons, 2013). The crème-de-la-crème of data sources are Environmental Product Declarations (EPDs). EPDs are effectively a standardized way of communicating the outcomes of a building material LCA conducted to a set of product category rules (BRE, 2013b). Despite standardisation, these LCAs are subject to a number of limitations, discussed in Section 2.4.2. The number of EPDs produced has expanded dramatically in recent years, and common international databases (e.g. Eco Health Data, 2014; International EPD® System, 2014) have launched to allow direct comparison of products. At the time of writing over 2000 verified EPDs had been produced globally; however, only a handful were from UK building product manufacturers. Many UK product manufacturers perceive insufficient demand from customers to warrant undertaking an EPD production process they see as complex and expensive. Consequently, EPDs remain a rare data source in most UK embodied carbon assessments. For example, on the school building assessment undertaken by Gavotsis and Moncaster (2015); the authors were only able to obtain EPDs for 5 of the nearly 200 building products used. One potential alternative to expensive EPD production, particularly for small manufacturers, is for industry advocacy groups to develop generic datasets for principal products and components with the production costs spread amongst their members. For example, the Wood for Good Lifecycle Database contains detailed data for the 17 most common UK timber and panel products and their associated proprietary products, such as adhesives (Wood for Good, 2014).

Where an EPD is not available, it is common to use generic embodied carbon factors from a number of other sources. These typically take the form of commercial, industrial or academic databases of material LCI information such as the Inventory of Carbon and Energy, or ICE database (Hammond & Jones, 2008), first published by the University of Bath in 2006 and last updated in 2011. This database is currently the most commonly used within the UK industry as it offers data for a wide range of building materials at no cost. Other alternatives that are commonly used include the subscription based Ecoinvent database (Swiss Centre for Life Cycle Inventories, 2013), and proprietary databases embedded in LCA software packages such as GaBi (Thinkstep, 2015) and the Athena Eco-calculator (Athena Sustainable Materials Institute, 2015). The BRE Green Guide (BRE, 2015) is commonly used by practitioners who are also undertaking a BREEAM assessment; and the Hutchins Blackbook cost guide has included supplementary carbon data since 2009 (Hutchins, 2011). The Hutchins figures are obtained from a variety of sources and are updated quarterly; however, a significant proportion of the initial figures were extracted from the ICE database. The growing dependence upon such generic datasets has garnered criticism as it increases exposure to several sources of error (Finnveden et al., 2009; Majeau-Bettez et al., 2011). These are expounded upon in Section 2.4.2.4. A small number of experienced specialist practices such as Sturgis Carbon Profiling, also maintain private databases and offer carbon accounting services. In the long term, it is likely that large consultancies and contractors will bring these skills in house, saving consultancy fees and minimising the dependence on these less transparent data sources.

The following section provides a review of the principal methods by which the environmental impacts of building materials are quantified – focussing upon the most prominent LCA methodologies. The review further details the shortcomings of existing approaches and outlines the current methodological state-of-the-art.

2.4.2 Embodied carbon assessment at the product level

The environmental impacts of building materials are typically quantified using LCA. A thorough LCA addresses the environmental aspects and potential environmental impacts - including carbon emissions - throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (International Organization for Standardization, 2006). LCA has been used worldwide as an environmental management tool since the 1960s; see Finnveden et al. (2009) for an overview of LCA and Menzies et al. (2007); Ortiz et al. (2009); and Sharma et al. (2011) for a review of applications in the construction industry. Typically, there are four phases in an LCA study:

» the goal and scope definition phase
» the inventory analysis phase
» the impact assessment phase
» the interpretation phase

Whilst extensive guidelines are available, and approaches to LCA are becoming increasingly standardized (with the majority conducted to ISO 14040), results for similar products vary significantly across studies. This is typically due to two primary differences: assumptions made during the respective phases of the assessment and the methodological approach adopted.

The goal and scope definition establishes the purpose, intended audience, functional unit, and system boundaries. Consequently, the depth and breadth of an LCA differs greatly depending on the goal. Often the goal and scope are in part determined by the level of resources available to the LCA practitioner (in terms of working time and data availability). This can result in limited system boundaries that do not encompass the full direct and indirect impacts of the product (Suh & Huppes, 2005). Much of the discrepancy in enumerated impacts between studies is a result of different boundaries being adopted during the scoping phase. It is particularly hard to identify the most important factors when selecting building materials, as many aspects of the life cycle are context specific and the service lives of materials are often long, highly variable or difficult to estimate (Norris & Yost, 2002; Treloar et al., 2000). Often these aspects of the life cycle have to be assumed and can be determinant in the outcome and product selection. In the inventory and impact assessment phases, assumptions made about product specification, manufacturing differences, data characteristics, energy supply and energy sources can also produce significant variations in estimated impacts (Menzies et al., 2007).

Furthermore, the underlying assumptions, system boundaries and limitations of each methodological approach are fundamentally different. The three main methodological approaches to LCA are: process-based LCA (P-LCA); environmentally extended or economic input-output based LCA (EIO-LCA); and hybrid approaches (H-LCA). The following sections provide a description of each method in turn. The requirements, principal advantages and disadvantages of each method are summarised in Table 3.

Table 3: Comparison of key LCA methodologies (expanded from Bilec et al., 2006; Suh & Huppes, 2005)

Methodology	P-LCA	EIO-LCA	Hybrid LCA
Requirements	Data representing commodity and environmental flows per process Access to one of a number of available LCA software tools or basic computational tools (e.g. Excel)	Data representing commodity and environmental flows per sector Access to one of a limited range of software tools (e.g. MIET, EIOLCA) or suitable computational software (e.g. MATLAB)	Data representing commodity and environmental flows per sector and process Suitable computational software for matrix inversion (e.g. MATLAB) and highly skilled operator
Advantages	Detailed analysis of specific processes Allows for detailed product comparisons Suitable for identifying process improvements	Boundary is defined as the entire economy Suitable for economy-wide, system LCA Generally based on publicly available data Reproducible results	Complete system boundaries Reduced uncertainty in final results Expresses feedback loops between product micro-level systems and macro-level economic structure*
Disadvantages	Subjective boundary selection Lack of comprehensive data in many cases Time and cost intensive Can require proprietary data Higher uncertainty in results owing to truncation errors	Aggregated level of data Identification of process improvements is difficult Imports often treated as home country products Results have high uncertainty Limited data for many countries Product use and end-of-life options not typically included	Requires large amounts of data Time intensive Complex process requires skilled practitioner

* advantage only experienced in integrated hybrid LCA

2.4.2.1 Process-based LCA

In P-LCA, the processes involved in a product life cycle are defined and the impacts of individual inputs into each process are assessed and summated. Typically, this covers only the first and second order inputs to a product with the remaining upstream processes either disregarded or compensated for using assumed impact factors. Generally, this results in a systematic truncation error, the magnitude of which will vary from product to product, but can be of the order of 20-60% (Lenzen, 2000; Majeau-Bettez et al., 2011). This error is unavoidable, as, in principle, all processes in an economy are directly or indirectly connected (Suh & Huppes, 2005).

Conducting a P-LCA is often a data-intensive endeavour and, consequently, many P-LCAs draw upon pre-existing databases containing generic LCI data gathered from a range of sources. These databases can be commercial, industrial or academic in nature, though there is a growing tendency to rely on national public databases. These have been developed for a variety of countries including Japan, China, Korea, India, Australia, Switzerland, Germany, Italy and Canada (Menzies et al., 2007). This increasing dependence upon generic datasets increases the susceptibility of P-LCAs to several sources of error. The data therein is often based upon production methods from firms operating in other regions, using different technology, during different time periods (Finnveden et al., 2009). In addition, some sectors are often sparsely represented in generic databases, resulting in skewed distribution of process detail by sector that can lead to errors of "*aggregation by proxy*" and "*sectoral background truncation*" (Majeau-Bettez et al., 2011).

2.4.2.2 Environmentally-extended input-output based LCA

EIO-LCA attempts to overcome the truncation errors and inconsistent boundary problems associated with P-LCA by considering the whole economy as a system boundary (Joshi, 2000). According to Finnveden et al. (2009), Input–Output Analysis is a field of economics that deals with the connections between industry sectors and households in a national economy in the form of supply and consumption of goods and services, formation of capital, and exchange of income and labour. It employs the methods developed by Wassily Leontief to transform national accounts data into an analytical framework consisting of a series of equations which each describe the distribution of an industry's product throughout the economy (Miller & Blair, 2009 p. 1). Typically this framework is extended to incorporate additional economic or physical factors. This technique has been in common use for several decades across a range of applications (Rose & Miernyk, 1989). Increasingly it has been used to tackle environmental problems, generally through linking environmental pressure data to financial transactions within an economy, in order to allocate impacts to particular products or sectors (Minx et al., 2009). See Lindner (2013) for a thorough review of the use of input-output analysis in environmental-economic life cycle assessment.

EIO-LCA's consideration of the whole economy as a system boundary makes it more suitable for comparison of options, particularly at the macro-scale. However, whilst it mitigates the principle problems of P-LCA it suffers unique errors that stem from the underlying proportionality assumption, aggregation uncertainties, and allocation uncertainties (Lenzen, 2000). These errors are related to both the input data and the underlying methodological assumptions.

The data, whilst more systematically gathered and more complete than process-based data sets, is still of dubious quality and often represents sectors at a coarse resolution (Suh & Huppes, 2005). It is also uncommon for imported products to be represented in detail and is therefore inappropriate for sectors or products with a high dependence on imports. This is a particular concern for the UK construction industry where many materials are imported and the sector resolution of available data is often coarse.

Three of the core methodological assumptions also result in significant errors. Namely that: each sector in the IO table produces only one good; production is proportional; and prices remain constant throughout (Lindner 2013). The assumption that each sector produces only one good makes EIO-LCA inappropriate for products that are atypical of a sector's output or for industries with a diverse range of products (Joshi, 2000). Whilst individual companies may produce a lone product, it is common in the construction sector for companies to produce a wide range of products with a complex mix of inputs. In addition, EIO-LCA is only suitable for assessing the pre-consumer stages of a product's life-cycle (Suh & Huppes, 2005; Joshi, 2000). The gate-to-grave period has a critical influence over the impact of most construction products, particularly when implemented in complex structures. However, whilst stand-alone EIO-LCA may provide insufficient detail to achieve accurate results, it can be combined with process information to form effective hybrid approaches (e.g. Wiedmann et al. 2011).

2.4.2.3 Hybrid approaches

The general framework of H-LCA approaches were first proposed in the 1970s (Bullard et al., 1978), though it took some years before they entered common use amongst LCA practitioners (Finnveden et al., 2009). Now they are considered state-of-the-art (Suh & Nakamura, 2007; Wiedmann, 2009). Through combination of the two methods previously described, H-LCA approaches endeavour to reduce the truncation error of P-LCA whilst increasing the product and process detail of EIO-LCA (Lenzen, 2000; Joshi, 2000). Their application to construction materials and processes was first proposed by Treloar et al. (2000), and has since been applied to a number of studies. A wide variety of hybrid approaches exist, though these are commonly grouped into four categories:

» Integrated hybrid analysis
» The Path Exchange Method
» Tiered hybrid analysis
» Input-output based hybrid analysis

Integrated hybrid analysis

Integrated hybrid analysis was first introduced by Suh (2004) to overcome the challenge of obtaining system completeness whilst preserving process specificity. It does this by integrating the computational structures of EIO and P-LCA within a consistent framework. In essence, this involves interconnecting a physical functional flow-based micro-level system model with a broader monetary, commodity-based economic system. Product LCA data is restructured into an input-output system, which is combined with defined upstream and downstream cut-off matrices and a broader economic input-output system to create one system combining functional flows with commodities (see Suh (2004) for a detailed description of this process). The approach is relatively complex and requires large amounts of data. However, it provides more complete system boundaries whilst preserving all available process level detail. The method also necessitates clear definition of cut-off boundaries. Both these factors are particularly useful for comparative LCA studies (Suh, 2004).

Whilst Suh introduced the methodology with a simple example in 2004, it was several years before Wiedmann et al. (2011) assembled sufficient data to undertake a thorough real world application. This calculation used a biregional supply and use framework alongside the Ecoinvent process database to assess the indirect environmental impacts of wind power in the UK. The authors compared the results of process-based, IO-based hybrid and integrated hybrid assessments for a 2MW offshore wind power plant. The results showed a doubling of life cycle CO_2 emissions from wind power when assessed using a hybrid approach, as opposed to a process-based approach. This increase was predominantly attributable to much higher embodied impacts for iron and steel (which increased by factors of 5 and 3 respectively). If this result is correct then it suggests that typical LCAs on which decisions are currently made have significantly underestimated the impacts of key materials. Alternately, if the results are incorrect, then it suggests that the data available for current hybrid techniques is grossly insufficient for establishing the impact of certain common materials of particular significance in construction applications. The authors of the study suggest that errors will stem from a number of sources. These include the conversion from physical to monetary units in the hybrid model, the mixing of temporal boundaries within the data, errors due to disaggregation of the input-output table and other parametric and systematic model errors. In spite of this, the authors suggest that the integrated hybrid method remains the most comprehensive approach. However, they stress that an IO-based hybrid method may still be preferred in practice owing to its simpler, quicker and cheaper implementation and its dependence upon, typically, more up to date data.

Whilst further applications of this approach are needed to assess its real world practicality, the underlying theory has received some further discussion and development (Suh & Huppes, 2005; Peters & Hertwich, 2006; Suh, 2006; Lenzen & Crawford, 2009). The significance of the upstream and downstream cut-off matrices is the subject of some debate, with Peters and Hertwich suggesting that the contribution of the downstream cut-off matrix would typically be negligible and therefore does not merit compilation (Peters & Hertwich, 2006). Suh countered by suggesting that the typically small contribution is no reason for automatically setting the term to zero and proposed a practical method for checking the importance of the downstream cut-off matrix before data compilation (Suh, 2006). Lenzen and Crawford suggest that whilst the integrated hybrid approach represents an improvement on preceding methodologies, it still necessitates incorporation of a large volume of process data, typically in the form of a large process technology database (Lenzen & Crawford, 2009). As a response to this, Lenzen and Crawford continued the work of Graham Treloar in developing a less data-intensive methodology, referred to as the Path Exchange Method.

Path Exchange Method

The Path Exchange Method (PXC) starts from a typical Structural Path Analysis (SPA) on conventional IO matrices. SPA essentially unravels the Leontief inverse through a series expansion of the direct requirements matrix in order to reveal the impacts caused by every order of consumption (Wood & Lenzen, 2009). PXC then improves accuracy by exchanging subpath-level IO information (based on economy wide average production) for corresponding specific process information. In cases where the process information is not directly equivalent to the IO information, a proportion of the item to which it applies is estimated from sales data and coefficients only replaced for this proportion. By exchanging only at a subpath level the method improves accuracy without disturbing the overall system (Lenzen & Crawford, 2009). Some of the unique advantages of this method include: its ability to capture feedback loops between the process and IO system elements; and that it can be conducted based on whatever industry specific information is available without dependence upon LCA database providers. Lenzen and Baboulet (2010) applied the PXC method to evaluate the environmental footprint of the University of Sydney. The authors demonstrated how application of such an approach could aid procurement officers in exploring environmental abatement opportunities throughout their supply chain. At the time of writing, to the author's knowledge no further detailed applications of this method had been published.

In the author's opinion the PXC method represents the current pinnacle of hybrid LCA practice, providing the most flexible and robust method of incorporating process based data into IO analysis. However, as identified by Wiedmann et al. (2010) in certain practical cases it may require many substitutions to achieve a satisfying outcome; and perhaps may be better applied after another hybrid analysis has been conducted. The method clearly requires further application to determine if this problem is isolated to particular sectors or a general concern. A further alternative is tiered hybrid analysis.

Tiered hybrid analysis

In this approach, direct (or 'downstream') requirements of a product during use and disposal phase are modelled with P-LCA, whilst higher-order (or 'upstream') requirements are modelled with EIO (Suh & Huppes, 2005). When rigorously applied, the approach proceeds from an initial first approximation through iterations incorporating increasing process detail and IO sector disaggregation until a satisfactory level of accuracy is achieved. A fundamental step in this approach is defining a boundary between downstream and upstream processes. Often the placement of this boundary is limited by data availability and study goals.

The tiered hybrid approach has been advocated for construction products (Treloar et al., 2000) and is viewed as a reasonably complete and relatively fast approach (Suh & Huppes, 2005). Whilst it is not as time-consuming and data-intensive as integrated hybrid analysis, neither is it as accurate. There is a risk of introducing significant error through incorrect boundary setting, and the division of the process-based and IO-based systems prevents the interaction between them being assessed in a systematic way (Suh & Huppes, 2005). Furthermore, there is a risk of double-counting the flows represented by process-based elements in the IO table. Though, methods have been proposed to correct for this double counting (Strømman et al., 2009).

Input-output based hybrid analysis

In this approach, one or more sectors of the IO model are disaggregated into new sectors. This can be achieved by a variety of means (Joshi, 2000; Lenzen, 2011). Disaggregating from existing industry sectors typically requires several pieces of information: the share of the product of interest in aggregate output of the original sector; an estimate of the technical coefficient vector; and data covering inter-industry sales of the product (Joshi, 2000). Often such information cannot be obtained or disclosed owing to commercial sensitivity (Allan et al., 2007). Iterative disaggregation of sectors could also be achieved based upon information from existing P-LCAs. However, this method often depends heavily upon additional information such as commodity prices, and typically requires significant assumptions to fill missing data or scale output to fit sectors (see Lindner

(2013 p. 48)). Thus, whilst the intention of this method is to produce finer resolution of pertinent sectors, it is often unachievable owing to data requirements.

Other hybrid analyses

In addition to the four main IO-hybrid approaches there have been limited examples of a so-called 'augmented process-based approach' (Bilec et al., 2006; Guggemos, 2003), wherein the method proceeds as follows. A process flow diagram is developed, the LCA boundary is determined and process inventory data is assembled. After analysis of the process data, EIO-LCA data are used to augment process data for specific major impact areas not quantified in the process data. In many respects this is in effect a more selective version of the hybrid approach described by Joshi (2000).

Whilst many of these hybrid approaches have been experimented with in academic circles, their use is not yet common in industry. This is primarily as the compilation and utilisation of such large-scale databases is both labour- and cost-intensive and requires significant practitioner skill (Lenzen et al., 2014). The majority of product LCAs remain process-based and suffer from fundamental truncation errors and mismatched system boundaries. However, efforts are underway to develop collaborative H-LCA databases for use by industry, such as the Australian IE-Lab (Wiedmann et al., 2013; Lenzen et al., 2014). It is hoped that the development of such approaches could reduce the time and effort required to assemble more accurate LCAs.

2.4.2.4 Shortcomings of current LCA approaches

In summary, each methodological approach suffers from unique shortcomings. P-LCA is highly susceptible to truncation errors; EIO-LCA has a limited range of applications where aggregation errors will not significantly affect results; and H-LCA approaches are typically data and time-intensive to assemble. The impact of these methodological shortcomings may be minimal when comparing products of a similar type and function with similar supply chains represented by comparable datasets. In such instances, results of a relative LCA between two products can be confidently used to inform product selection. However, in practice, engineers and architects must often decide between products that are not directly substitutable and are produced by thoroughly different supply chains. For example, the decision to build a structure using a steel, concrete or timber frame. In such instances, practitioners often resort to comparing absolute values provided by product manufacturers. Such LCAs, based upon absolute values, suffer from a number of further shortcomings. Let us consider these in turn.

Selection of functional unit

The selection of an appropriate functional unit is crucial in determining the outcome of any LCA. In the case of building products, common data sources usually express the impacts per unit volume or mass. However, such a presentation is not particularly helpful in product selection on a building project, as a kilogram of each product may exhibit different physical properties and serve different purposes. For example, one kilogram of steel and one kilogram of timber will not bear the same load. Some authors (e.g. Ashby, 2009) have consequently advocated presenting results that have been normalised with respect to a relevant mechanical property, such as compressive strength. Others (e.g. Purnell, 2012) argue that component purpose and geometry are critical and that "materials must be compared on the basis of their embodied carbon per unit of structural performance, per unit component length, for meaningful comparisons to be made". Others (e.g. Sathre et al., 2012) argue that functionally equivalent versions of complete buildings is the only appropriate functional unit for comparison. In this author's opinion the later approach is the only sensible approach in the majority of cases. Normalisation of materials relative to a single property, as suggested by Ashby, fails to capture the multiplicity of functions that a material plays. For example, the material selection for a wall will also influence thermal and acoustic performance, the building weight and foundation sizes. The consequent changes in design that may be required to deliver comparable performance across all these factors cannot be captured by a single unit of structural performance within a particular component. The approach of Purnell suffers from similar limitations, and also implicitly suggests that components achieving high utilisation ratios will always be preferable. In many cases, particularly for lightly loaded structures such as housing, a building constructed of low carbon materials with low utilisation ratios can be lower in total embodied carbon than a building produced from high carbon materials with high utilisation ratios. The study by Purnell also exhibits another common shortcoming of LCA, a dependence upon outdated input data.

Quality of input data

All LCAs are highly dependent on the quality of input data, which is often difficult to obtain. Consequently, time limited practitioners regularly depend upon readily accessible datasets which are often outdated. For example, Purnell's 2012 study draws upon data from a version of the ICE database published in 2008. This version of the database in turn uses data produced several years prior to publication. Consequently, the figures used by Purnell vary substantially from figures published in recently verified EPDs. For instance, Hill & Dibdiakova (2016) demonstrate in a review of recent wood EPDs that glulam is typically around 0.4 kgCO_2e/kg; substantially less than the 0.7 kgCO_2e/kg used by Purnell. Indeed, Hill & Dibdiakova's review highlighted that for all wood products except fibreboard, the ICE database figures were substantially greater than those found in recent EPDs.

The ICE database has not been updated since 2011 but, despite this, remains the UK industry's standard data source with over 17,000 downloads. The use of such outdated data can provide misleading results, particularly when it is used to produce generic recommendations, such as Purnell's rule of thumb recommendations for application of steel, concrete and glulam.

End of life scenarios

Purnell's paper also draws attention to another common cause of dispute between material producers and LCA practitioners – determination of appropriate end of life scenarios. Building decommissioning regimes decades into the future are inherently unpredictable; however, the substantial impacts of different means of post-use treatment and disposal of materials is worthy of consideration. Without consideration of such impacts, an LCA should be considered incomplete. To illustrate the challenges associated with determining appropriate scenarios, let us consider the example of a timber building product. When removed from a building the product may be either re-used in another building; recycled into particleboard or a similar secondary product; incinerated for energy recovery or sent to landfill. Each of these choices incurs different impacts. When considered as suitable for re-use it is common practice to include credits for the displacement of virgin timber that may otherwise go into production of the new product. Similarly, when sent for recycling or incineration, credits may be included equivalent to the avoided impacts of producing woodchips from virgin softwood or using coal for combustion. When landfilled, assumptions must be made about the location of the disposal site and the waste management practices used. Clearly this raises a number of questions. First, which scenario should be considered most plausible if results may determine product selection? Secondly, should the avoidance of hypothetical future consumption be allocated emissions credits in the present day? Thirdly, should a benefit be assigned to the temporary sequestration of carbon throughout the timber product's life even if it is ultimately released to the atmosphere through incineration or landfill degradation? These questions remain the subject of ongoing debate, with a broad range of accounting methodologies and alternative assumptions under consideration (Brandão et al., 2013). Irrespective of the particular options that are chosen by consensus, all these questions must ultimately be resolved through a subjective choice of system boundaries and allocation of emissions.

Best current practice considers a range of potential outcomes, for example, presenting results for each of the four end of life scenarios for the timber product (e.g. Wood for Good, 2014). Similarly, results can be presented with and without credits for avoidance of future consumption and sequestration. Such an approach allows the practitioner responsible for product selection to make an informed, albeit subjective, choice. Unfortunately, in many cases, product manufacturers mask such assumptions and only present headline figures to decision-makers, with the consequence that product selections are often made with incomplete, inaccurate or incomparable information. The proliferation of EPDs with standard product category rules, should improve the transparency of product data (Ibáñez-Forés et al., 2016). This should be accompanied by dissemination of accessible guidance for industry practitioners (e.g. Hill, 2016), and the increased standardisation of accounting approaches (e.g. through continued revisions to PAS 2050).

In the absence of such information, many construction sector practitioners have turned to a growing number of building assessment tools for guidance (Ding, 2008). See Haapio & Viitaniemi (2008) for a critical review of available assessment tools. Some additional tools have been launched since this publication; however, those discussed by Haapio and Viitaniemi remain the most prominent examples. Whilst these tools have been successful in instilling environmental awareness in the sector, they suffer from a number of flaws. Often the underlying assumptions are not available for the user to scrutinize and results still depend heavily upon interpretation by the end user.

All of these issues give rise to the view that LCA is *"a flawed tool that cannot deliver what it promises"* (Joshi, 2000). Yet, in spite of these concerns, LCA remains the best way of assessing the embodied carbon in building products, and in turn the embodied carbon in buildings. Over time more sophisticated methodologies will be developed, more primary data will be gathered, and presentation of results will be further standardised. However, LCA will always be dependent upon certain subjective choices related to the boundaries of assessment and the prediction of future outcomes. With a sizeable market for green construction products at stake, these choices will likely remain a subject of dispute between material producers. The challenge for LCA practitioners is to ensure that all choices are transparently presented and clearly justified.

The following section considers results from the application of LCA to buildings, in particular focussing on the relative proportions of whole life cycle emissions attributable to operational and embodied carbon.

2.5 The balance between operational and embodied emissions

The experience of practitioners conducting building LCAs throughout the 1990s was that "*determining embodied energy was extremely difficult and costly*" (Shipworth, 2002). Early studies also suggested that operational energy and emissions were typically many times greater than embodied emissions. For instance in 1991, the BRE suggested that embodied energy could account for less than 3% of the whole life total for a typical 3-bed detached house (BRE, 1999). This combination of perceived insignificance and practical difficulties deterred many from undertaking embodied energy or carbon assessments. Consequently, for many years, the industry retained a perception that embodied emissions were insignificant, and that carbon reduction must focus on operational emissions.

The last two decades have seen a tremendous focus, driven by accompanying regulation, on reducing operational energy use; principally by improving the building fabric to achieve better thermal performance. This has necessitated an increased use in materials, as better performing wall systems are typically thicker and more complex (Smyth et al., 2008). This change in fabric, combined with improvements in the energy efficiency of equipment and appliances has led to significant reductions in operational emissions. At the same time, embodied emissions have increased due to the profusion of building technologies and the adoption of higher performance building fabrics. These two factors have shifted the balance between operational and embodied emissions. For instance, a study of typical contemporary 3 and 4-bed UK houses found that embodied emissions now make up 31-42% of total life cycle emissions (NHBC Foundation, 2012). Similar studies in other types of structures have demonstrated embodied carbon can contribute as much as 90% of whole life emissions (Sturgis & Roberts, 2010).

Ibn-Mohammed et al. (2013) provided a recent review of life cycle assessments and concluded that "*a trend that may be observed is the increasing proportion of embodied emissions*". The authors predicted that the share of life cycle emissions attributable to embodied carbon will increase further with reductions in operational emissions owing to improved operational performance and reductions in the carbon intensity of the electricity supply. Meanwhile, substantial absolute increases in embodied carbon can also be expected with an anticipated growth in building activity. Scenarios from the GCB Low Carbon Routemap for the Built Environment suggested that embodied carbon may constitute nearly 40% of total built environment emissions by 2050 (GCB, 2013b p. 4). These trends led Grinnell et al. (2011) to conclude that "*as gains in operational energy reduction are realised, embodied energy of the construction, maintenance, refurbishment and disposal cycle will become increasingly important in making further progress [towards carbon reduction targets]*". Similarly, the GCB Routemap authors argued that "*capital carbon must start to be addressed in tandem with operational carbon*" (GCB, 2013b p. 4).

2.6 The case for addressing embodied emissions

It can be argued that, aside from being essential if sector carbon reduction targets are to be met, strategies targeting reductions in embodied emissions may be preferable to those targeting operational emissions, as they offer more immediate and predictable savings (Ibn-Mohammed et al., 2013). The benefits of lower embodied carbon choices can be readily quantified at the design stage and are less dependent on unpredictable factors, such as future building occupancy and use. Building life expectancies, particularly for commercial structures, are frequently overestimated. This results in predicted savings in operational emissions, which notionally offset increased embodied emissions decades into occupancy, never being realised in practice. Similarly, the dependence of current strategies on projected carbon savings in the occupancy phase leaves them more susceptible to widely documented performance gap problems (Zero Carbon Hub, 2014). For instance, the Innovate UK Building Performance Evaluation Programme showed through a comprehensive study of 101 recently built projects that actual operational emissions are still often multiple times the anticipated design values (Bunn et al., 2013).

The importance of addressing embodied emissions further increases when taking account of the temporal allocation of emissions. The prevailing advice of climate scientists is that the world must act in the next two decades to prevent dangerous levels of change (IPCC, 2014). Operational emissions savings projected decades into the future may already come too late to prevent catastrophic changes associated with global temperature rises over 2°C; a target many climate scientists predict will be exceeded (Peters et al., 2012). As cumulative emissions, not annual emissions, are the critical component in preventing such unacceptable levels of climate change (Matthews et al., 2012), some researchers have argued that a greater weighting should be attached to current rather than future emissions savings in economic analyses and policy making (Rhys, 2011). Meanwhile current policy has taken the reverse approach, basing evaluations on anticipated rises in the value of carbon in coming decades, essentially devaluing the benefits of early action. Indeed, the general approach of most international mitigation efforts has been to set targets for individual years that should be delivered through market-based approaches with progressively tightening carbon caps. Whilst intended to reduce immediate impacts on consumer prices, this approach establishes a price signal that values future carbon savings more highly than present savings, delaying investment in mitigation measures and encouraging earlier discharge of unavoidable emissions. This fundamentally ignores the declining social cost of carbon over time, which recognises that the damage of a tonne of CO_2 emitted today is greater than a tonne emitted in the future. Such an approach also ignores the option value of achieving early reductions, i.e. the time it buys for further development of technological and policy solutions. If these higher social costs and the ignored option value could be captured in current prices, the immediate abatement of embodied emissions in buildings would likely appear a more financially attractive option than the future abatement of operational emissions. Whilst these ideas have been explored in other fields, few quantitative studies have considered the temporal allocation of emissions in building assessments and the associated marginal costs of abatement measures.

Though not considering arguments surrounding cost, Heinonen et al. (2011) demonstrated that the swift release of emissions, or 'carbon spike', associated with construction phase emissions can dominate life cycle emissions in the time horizon relevant to adopted climate mitigation goals. This conclusion led the authors to subsequently question the merits of building new energy-efficient developments as a means of climate change mitigation (Säynäjoki, Heinonen, & Junnila, 2012). Other authors have also suggested that anticipated demand for infrastructure development will inevitably account for a considerable portion of remaining cumulative carbon budgets (Müller et al., 2013). This portion would substantially increase if the impacts of maintaining existing infrastructure were also enumerated.

With predicted growth in UK construction activity potentially yielding a sizeable carbon spike, it is pertinent to ascertain whether the aggregate embodied emissions of these construction activities are compatible with UK climate mitigation targets. In order to do this, it is first necessary to enumerate the aggregate embodied emissions associated with UK construction activity. Chapter 3 critiques previous attempts to compute such an estimate, and provides a new estimate. Chapter 6 continues by exploring the embodied emissions associated with anticipated building activity.

2.7 Summary and discussion

This chapter has provided a state of the art review of embodied carbon assessment, considering recent methodological developments alongside typical industry practice. Drawing together an extensive pool of academic and industry literature, it has highlighted a number of shortcomings in current approaches and areas requiring further research. In short, whilst over recent years the industry has expanded guidance and raised the profile of embodied carbon, the response remains piecemeal. Few clients are requesting embodied carbon assessment and policy makers have yet to introduce meaningful requirements or incentives.

Despite the introduction of EN15978, approaches to assessment are still far from standardised with practitioners using a wide variety of system boundaries and assumptions. There remain significant gaps in existing guidance and consensus has yet to be reached on a number of accounting issues, such as the benefits of carbon sequestration. Despite recent progress, product manufacturers and practitioners still frequently fail to clearly distinguish the impacts of subjective decisions in the presentation of LCA results. The presumed service lives of structures are also rarely subjected to scrutiny or sensitivity analysis. Few assessments account for the temporal significance of embodied emissions, instead equally valuing projected carbon savings from operational emissions decades into the future. Furthermore, the integrated tools that will support a shift from retrospective to proactive building

LCAs as part of the design process still require substantial development and additional incentives for adoption.

There remain many challenges in gathering accurate data on site, which can severely restrict the range of products included in a carbon assessment. Accessing product footprint data is also difficult, with UK product manufacturers yet to develop EPDs on the scale of their continental counterparts, and many practitioners dependent upon generic databases. These databases are largely based upon process-based LCAs with limited system boundaries and often represent production methods from firms operating in other regions, using different technology, during different time periods. Though many practitioners are using these databases, few fully understand their limitations, and even some academic authors are making general recommendations on the basis of outdated information representing a small number of producers.

The earliest building level LCAs consistently suggested that embodied impacts were relatively insignificant, ingraining this perception in the minds of many practitioners. Practitioners and policy makers still often underestimate the importance of embodied carbon for the reasons Moncaster (2012) notes:

"The combined impact of using a process-based analysis, of focusing on the materials phase only, and of displaying embodied carbon as spread equally over the lifetime of the building, all have the result of reducing the perception of embodied carbon. These choices of calculations, and of ways of portraying the results, reduce the perceived impact of embodied carbon, and support the conclusion that a focus on the operational phase only is a 'rational' decision. The complexity of the calculations and lack of raw data make this difficult to disprove."

This 'rational' decision has restricted policy makers and practitioners' focus to operational emissions and prevented comparable regulatory requirements emerging for embodied emissions. A common perception remains that regulation cannot emerge without resolution of "*long established challenges such as data, system boundary, uncertainties, methodological issues, lack of consistent framework, etc.*"(Ibn-Mohammed et al., 2013). However, it should be remembered that similar concerns were expressed about the calculation of operational emissions when regulatory requirements were first introduced. Indeed, many of these objections persist to this day despite widespread acceptance of operational carbon assessment within the industry. A perfect assessment method should not be seen as a prerequisite for the regulation of embodied carbon. Indeed, simple measures such as mandating whole life carbon assessment on projects over a certain size (similar to the Dutch government) could be introduced in short order with minimal changes to current practice. Such a policy could indirectly motivate reductions and provide benchmark data for later regulations. Whilst some within the industry will argue that assessment methods are not yet sufficiently developed for regulation, many individuals intimately familiar with the intricacies, challenges and uncertainties of embodied carbon assessment such as Moncaster and Gavotsis (2015) argue that "*now is the right time for the calculation of cradle-to-grave/cradle embodied carbon impacts to be legislated, followed by increasing reduction requirements*".

Given the severe carbon reductions required and the project specific nature of the proposed abatement solutions, responses at different scales – national, regional, community, individual project, and individual actor – may be necessary. Such a combination of multi-level and multi-actor responses could be the most effective and politically resilient solution; however, the increased complexity of compliance may equate to additional cost for construction firms. A diverse array of local authority requirements and emerging discrepancies between the devolved administrations already pose a distinct risk of developing highly fragmented policy. If the UK is to avoid a repeat of the last decade's collection of short-lived under-delivering policies, then policy makers must adopt a new approach. Given the uncertain nature of future demand for building stock, the volatile financial climate, and the UK's 5-year political cycles; it is imperative that any policies are adopted as part of a long term adaptable strategy that is resilient to changes in politics and personnel, and robust to futures that cannot easily be hypothesised. One potential solution for policy makers is to consider their options as part of a series of dynamic adaptive policy pathways, as described by Haasnoot et al. (2013). This approach is further explored in Chapter 7.

In the meantime, current drivers are inadequate to promote widespread embodied carbon assessment and abatement. Although embodied carbon has increasingly been regarded within the industry as an overlooked aspect of the broader green building agenda, the theoretical business case for embodied carbon reduction has yet to be conclusively supported by market data. Information on the relative costs of embodied and operational emissions mitigation is sparse, and price signals from key mitigation policies have failed to reflect the greater value of early action. More broadly, there remain "*insufficient demands or active drivers for change to engage clients*" and a key challenge in "*changing industry attitudes when legislation is not forthcoming*" (UKGBC, 2014a). In the absence of substantive drivers and coordinated industry action, the contribution of embodied carbon mitigation to ambitious sector and national emission reduction targets remains unclear.

3. Evaluating the embodied carbon associated with UK construction industry supply chains

Parts are not to be examined till the whole has been surveyed

Samuel Johnson

3.1 Introduction

Whilst the previous chapter reviewed the practice of embodied carbon assessment at the project and product level, this chapter sets out the aggregate embodied emissions associated with UK construction activity. The two prominent UK sector level estimates of embodied carbon produced to date are critiqued and a new estimate of supply chain emissions is presented. The new estimate is considered from multiple perspectives: by final product, intermediate activity and spatial origin.

Analysis of the new estimate identifies a need for substantive reductions in emissions from materials extraction, manufacturing and production to achieve sector level climate mitigation targets. Subsequent sections therefore explore short-medium term opportunities within production of key materials and argue that sector targets will necessitate a reduction in the aggregate use of the most carbon-intensive building materials.

The chapter begins by describing the challenges inherent in estimating aggregate sector impacts. Section 3.3 contains a detailed critique of prior attempts. Section 3.4 presents a new estimate. Section 3.5 explores the opportunities for reducing emissions from material production processes. Section 3.6 sets out the case for a reduction in the overall use of carbon-intensive materials. Section 3.7 concludes with a brief summary and discussion.

3.2 Embodied carbon assessment at the sector level

Owing to the poor granularity of data currently gathered for the UK's territorial and consumption-based emissions accounts, it remains exceptionally difficult to swiftly and accurately distinguish the aggregate embodied impacts of construction activity.

Official territorial statistics based upon the basket of 6 GHGs included under the Kyoto Protocol put the UK's total GHG emissions at 568.3 $MtCO_2e$ in 2013 (DECC, 2015a). These statistics are commonly disaggregated into 8 sectors: energy supply, transport, business, residential, agriculture, waste management, industrial process and public sector. However, the impact of construction and construction products typically spans a number of these sectors. In addition, a large volume of construction products are imported, including over half the UK's steel demand, over a million tonnes of cement and nearly all aluminium. The impacts of producing these materials are not included in territorial accounts.

The UK's consumption-based accounts estimate total emissions attributable to UK consumption of 863.9 $MtCO_2e$ in 2012 (DEFRA, 2015). These consumption based figures can be loosely attributed to sectors based upon Standard Industrial Classifications (SIC). A summary of this classification system can be obtained from the Office for National Statistics (ONS 2011). Within these figures, the main SIC classification associated with construction activity, SIC 58, is attributed a footprint of 40.5 $MtCO_2e$ in 2012, equivalent to 5% of the total UK footprint. However, this figure solely reflects emissions associated with output of the construction industry, not all construction activities. This means of accounting excludes direct transactions between building material producers and households. For example, materials such as cement can be purchased directly by households for conducting basic home repairs and simple construction works. At no point in that transaction would the material pass through the construction industry and therefore would not be captured within the national accounting figures that form the basis of the footprint estimate. Thus the emissions captured in SIC 58 really represent a subset of the total emissions from construction activities.

As a consequence of these issues it is impossible to easily distinguish the true impacts of construction in the UK's official emissions accounts.

3.3 Previous estimates of embodied carbon in UK construction

Two attempts, summarised in Table 4, have been made to estimate the emissions that fall within the influence of the UK construction sector (BIS, 2010; GCB, 2013b). Both attempts were made in support of high profile industry reports, discussed previously in Section 1.4. Both estimates concluded that operational emissions are the dominant component and thus warrant the principal attention of policy makers. However, the means by which the estimates of embodied emissions were computed deserves scrutiny.

The first attempt, made in support of the IGT report: Low Carbon Construction, estimated that construction could influence around 47% of total UK CO_2 emissions (HM Government, 2010). Of this total an estimated 17% were attributable to embodied emissions, of which 87% came from the manufacture of materials (BIS, 2010). However the estimation approach, described in Table 4 overleaf, suffered from two important deficiencies. Firstly, no attempt was made to update the 2004 figure for imported emissions to the 2008 base year adopted in the report, despite the fact that this figure had grown by 49% in the preceding 4 years (Wiedmann et al., 2008). Secondly, the assumption that 100% of domestic material production from some of the sectors included is used exclusively for construction in the UK is highly questionable, and the means by which the figures were aggregated will inevitably result in some degree of double counting. These factors would imply a possible overestimate in total domestic emissions. However, this is more than counterbalanced by the underestimate in the figure attributable to imports due to the use of 2004 instead of 2008 data. Retrospectively comparing the data for these years shows a nearly 20% increase in emissions attributable to imports between 2004 and 2008. Once emissions attributed to design, distribution and operations

Table 4: Previous estimates of GHG emissions attributable to the built environment

Methodology	Innovation and Growth Team (BIS, 2010)	Green Construction Board (GCB, 2013)
Total emissions attributable to the built environment	298.4 $MtCO_2$ in 2008 Of which 51.9 $MtCO_2$ embodied	190 $MtCO_2e$ in 2010 Of which 33.6 $MtCO_2e$ embodied
Ratio of embodied: operational emissions	17:83	18:82
Breakdown of embodied emissions	Product manufacture: 45.2 $MtCO_2$ Distribution: 2.8 $MtCO_2$ Operations on-site: 2.6 $MtCO_2$ Design: 1.3 $MtCO_2$ Refurb/demolition: 1.3 $MtCO_2$	Materials extraction, manufacturing and production: 18.1 $MtCO_2e$ Distribution: 3.4 $MtCO_2e$ On-site activities: 6.7 $MtCO_2e$ Design services: 1.7 $MtCO_2e$ Other: 3.7 $MtCO_2e$
Methodology	Domestic: sum of emissions attributable to the domestic production of 'Wood and wood products', 'Paints, varnishes, printing ink etc.', 'Rubber products', 'Plastic products', 'Glass and glass products', 'Structural clay products, cement, lime and plaster', 'Articles of concrete, stone etc.', 'Metal products', plus 28% of the total for 'Iron and steel, non-ferrous metals, metal castings' based on figures from the Environmental Accounts. Imports: 2004 embodied emissions from imports from Sector 88: 'Construction' of the University of Leeds and CenSA two region MRIO model.	The entire capital carbon allocation is extracted solely from Sector 88: 'Construction' of the two region University of Leeds and CenSA MRIO model for the period 1990-2009. This is then apportioned into 'Infrastructure', 'Non-domestic buildings', and 'Domestic buildings' based on the financial value of construction output during this period.

on site were included, total embodied emissions for 2008 were estimated in the IGT report to be 51.9 $MtCO_2$.

The GCB chose to adopt an alternate approach for their estimation of 'capital carbon' within the 2013 Low Carbon Routemap for the Built Environment (GCB, 2013b). The term capital carbon is the preferred terminology for embodied carbon in the infrastructure segment of the industry because it accords with the concept of capital cost. The GCB definition of capital carbon included "*direct process emissions and indirect emissions from the manufacture and production of UK and imported construction materials and products, emissions from the transport of materials, emissions associated with professional services in support of construction, and all construction and demolition works on site*". The GCB approach was simply to extract the construction sector emissions from the consumption based accounts. Thus the GCB figure was likely an underestimate due to its exclusion of emissions attributable to direct transactions between material producers and households. This means of estimation resulted in total embodied emissions of less than 39 $MtCO_2e$ in 2008 compared with the IGT estimate of 51.9 $MtCO_2$. Clearly, the assumptions made in allocating embodied emissions to construction can result in a considerable difference in the calculated figure (of the order of 33%). Ultimately, the GCB estimated that the broader built environment influenced emissions of 210 $MtCO_2e$ in 1990 and just over 190 $MtCO_2e$ in 2010.

The GCB Routemap also outlined future projections of emissions under a number of scenarios. In order to estimate the implications of these scenarios the total sector capital carbon emissions were apportioned to 'infrastructure', 'domestic', and 'non-domestic' buildings. This allocation was simply based on the financial value of output of the three categories. This approach implicitly assumed the same material intensity across all categories and throughout the analysis period. Does a bridge really produce the same emissions per £ of output as a house? Was the material intensity of producing a house the same in 1990 as in 2010? This simplistic assumption potentially undermines the estimates of future emissions that stem from manipulation of these three totals. In the case of domestic and non-domestic building stock, the '80% Carbon Reduction Scenario' also assumes that building performance will improve drastically over time with the use of better building fabrics without any corresponding increase in embodied emissions. The implicit assumption that new structures with improved performance will be produced with the same capital carbon input as contemporary structures is likely incorrect. Furthermore, the report's assumed growth in infrastructure spending is minimal and predicated largely on historical trends from 1980-2011, not current considerations. This includes assumptions of no change from current road investment levels and increases of 1.7% in railways and 9% in electricity to 2017 with only 1.2% thereafter (GCB, 2013b p. 35). These figures fall below levels already set out for in the National

Infrastructure Plan and Investment Pipeline (HM Treasury, 2014). Even under these optimistic assumptions the scenario that achieves 2050 targets assumes carbon capture and storage (CCS) will contribute in the materials industry within the next 7 years and will be universally deployed by 2050. At the time of writing, CCS has not yet been fitted on any materials production facility in the world. It appears highly unlikely that this will change in the near future (Li et al., 2013). The scenario also envisages improvements in material production efficiencies of 43% for metals, 31% for concrete, 61% for brick and 30% for glass by 2050. The opinion of this author and others is that improvements of this magnitude are currently inconceivable. The reasons for this are further explored in Section 3.5. The future scenarios are also based upon incredibly optimistic grid decarbonisation scenarios provided by DECC (184 gCO_2e/kWh by 2020 falling to 105 gCO_2e/kWh by 2030) (GCB, 2013b p. 27). This projection is nearly half that anticipated at the time by the CCC (323 gCO_2e/kWh by 2020) (CCC, 2010 p. 243). To put this in context, the grid average intensity in 2014 was 442 gCO_2e/kWh (CCC, 2015b p. 45). Considering all these concerns, there is good reason to believe the situation is even more desperate than suggested by the already "*challenging*" 80% reduction scenario.

3.4 New estimate of embodied carbon in UK construction

In this section an improved estimate of the embodied emissions associated with UK construction is presented, which makes a number of corrections to the IGT and GCB approaches. Section 3.4.1 describes the methodology adopted. Section 3.4.2 details results from the new model. Section 3.4.3 provides a brief comparison with results from an alternative approach.

3.4.1 Research methodology, objectives and boundaries

The objective is to satisfy the first project research aim of conducting a robust evaluation of the embodied carbon emissions associated with the UK construction sector supply chain.

The boundary adopted for the sector level assessment is the full consumption-based supply chain emissions irrespective of country of origin. This is commonly considered as Scope 3 emissions in GHG reporting protocols. This is the most appropriate boundary as many construction products are sourced from overseas and GHG emissions contribute to climate change irrespective of the location in which they are emitted. The emissions associated with the production of these building products can be considered within the influence of the UK industry as specifiers can choose between many producers and other practitioners can reduce material use through design choices and on-site practices.

The evaluation is conducted from a top-down perspective using a multi-region environmentally-extended input-output model (MRIO). A brief overview of this modelling approach is provided in Section 2.4.2.2 and the particulars of this model are described in the following paragraphs. The alternative bottom-up approach to estimating sector level embodied emissions would be to summate total emissions from a combination of product LCA and consumption data. A top-down MRIO approach was preferred for several reasons. First, IO's consideration of the whole economy as a system boundary prevents truncation errors of the sort discussed in Section 2.4.2.2. Secondly, the MRIO approach does not require gathering of primary consumption and LCA data for the vast range of products consumed by the industry. The MRIO approach also includes emissions associated with transport and on-site activities. It would be impossible to gather primary data from all construction sites, or even a representative sample, to estimate these emissions from a bottom-up approach. Furthermore, once the model is constructed, the MRIO approach involves relatively simple calculations and benefits from the availability of time series data. In Section 3.4.3, results from the MRIO approach are also compared with a bottom-up estimate using consumption volumes and product LCA data compiled simultaneously by another author (Doran, 2014). This comparison shows good agreement.

The model used is an updated version of the UK MRIO model developed at the University of Leeds for DEFRA (Wiedmann et al., 2008). The model is structured around data from the Office of National Statistics (ONS) with trade data sourced from the Eora model developed at the University of Sydney (Lenzen et al., 2012). Four regions are considered: the UK, the rest of the EU, China and the Rest of the World (ROW). Supply, Domestic Use and Domestic Final demand tables from ONS at 106 sectors (based around SICs) make up the domestic section of the model. UK imports to intermediate demand are also available from ONS by sector but the data on the source sectors and regions supplying these imports is not. Using the UK sector totals as a constraint, the intermediate flows are distributed using proportions from Eora. The final demand of UK consumers for imported goods is also calculated using Eora proportions and UK product total constraints. A similar method is used to proportion exports from UK industry to foreign intermediate and final demand. Finally, Eora supplies trade between the rest of the EU, the rest of the world and China and their final demand to complete the model.

The National Accounts produced by the ONS provide GHG emissions totals by the 106 UK sectors. Emissions for foreign sectors are taken from Eora. Data in Eora is not supplied at the 106 sector classification used by the UK. Instead, Eora uses a heterogeneous sector classification that reflects the original input-output data submitted by individual national statistics agencies. Each of the sectors reported by the 185 regions (the 186 Eora regions minus the United Kingdom) in Eora are mapped to the UK's 106 sector classification. For some cases sectors are aggregated to map to UK sectors, however often Eora sectors have to be disaggregated to two or more UK sectors. Sector disaggregation calculations use the UK's total output as a weight.

The UK MRIO model used for this analysis also differs slightly to the model used to calculate the UK consumption based accounts for DEFRA. The model used here ensures that spend representing UK final demand for an imported product is constrained by product proportional spends observed in the UK's national accounts. The Eora model is then used to proportion spends by import region. By contrast, the DEFRA model takes total final demand spend on all imported products and uses proportions from Eora to calculate by product and region. Additional figures have been added to the model total for the construction sector to compensate for the accounting anomaly whereby transactions made directly between material producers and households do not appear within the influence of the construction sector. A short explanation of this correction follows.

The COICOP classification of household expenditure by purpose, developed by the United Nations Statistics Division, was used to estimate levels of household final demand that corresponded to direct expenditure on construction materials. This was done by computing the proportion of total household expenditure by product category under classification '04.3 Maintenance and repair of the dwelling'. Proportions were established for each year across the following product categories: 'wood and products of wood and cork, except furniture; articles of straw and plaiting materials'; 'paper and paper products'; 'paints, varnishes and similar coatings, printing ink and mastics', 'rubber and plastic products', 'manufacture of cement, lime, plaster and articles of concrete, cement and plaster', 'glass, refractory, clay, other porcelain and ceramic, stone and abrasive products', 'other basic metals and casting', and 'fabricated metal products'. These proportions were then used to redistribute errant material production emissions to construction. This results in a correction of 4.93 $MtCO_2e$ (~9% of total embodied emissions) in the average year. These figures were computed for each year from 1997-2010. The figure for 2011 was based upon the proportion from 2010 as the ONS implemented fundamental changes to their methodology to comply with ESA95 for their 2013 release of the 2011 figures (ONS, 2013a). This new classification method effectively excludes all expenditure on repair and maintenance from owner-occupiers and is thus no longer suitable for this purpose.

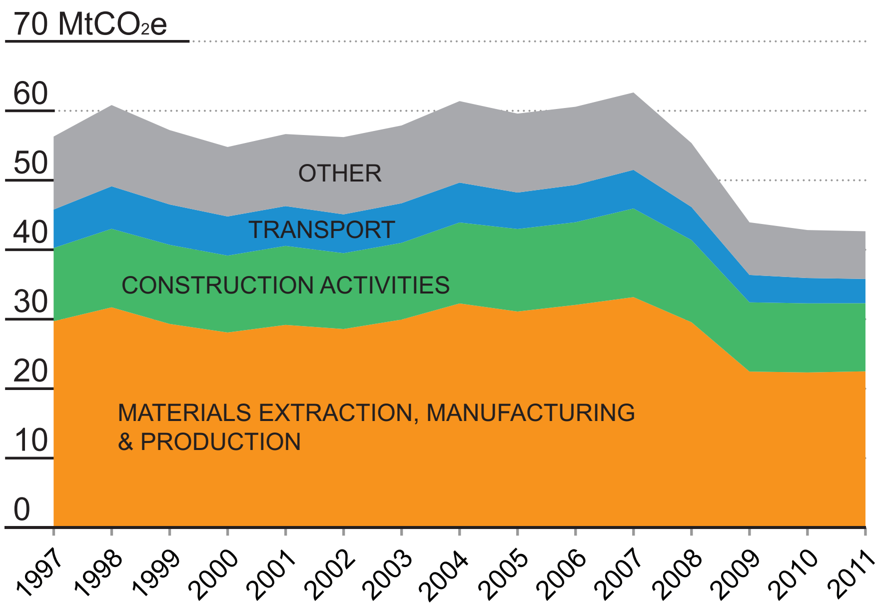
Using this model annual estimates of embodied emissions associated with construction were computed for 1997-2011. These results were analysed from a number of perspectives, and visualised in Figures 8-10. The means by which each figure was produced is discussed in Appendix A. In short: Figure 8 considers the distribution of emissions by intermediate activity; Figure 9 considers their spatial origins; and Figure 10 the emissions attributable to each end product. Finally, Figure 11 combines these perspectives. Let us consider them in turn.

3.4.2 Results

First, at an overall level, Figure 8 shows that total embodied emissions associated with construction in 1997 were approximately 56.2 $MtCO_2e$. This figure grew to 62.6 $MtCO_2e$ by 2007, representing 6% of the UK's total carbon footprint. To put this in context, this is roughly equivalent to tailpipe emissions from all the cars in the UK, which totalled 62 $MtCO_2e$ in 2013 (CCC, 2015b p. 125). Over the following years the global financial crisis and the corresponding UK recession resulted in an unprecedented drop in construction output. Quarter2 2008 to Quarter2 2009 featured the largest annual drop in construction output on record, with Quarter3 2011 to Quarter3 2012 being the fourth largest (ONS, 2013d). This resulted in embodied emissions falling to only 42.6 $MtCO_2e$ by 2011. Throughout the analysis period total emissions generally tracked increases and decreases in construction activity. This suggests that anticipated future increases in construction activity could also yield increases in emissions. Given that new work in the construction industry increased by nearly 20% in the period from 2012 to June 2015 (ONS, 2015a), it is likely that, once available, figures for this period will show an upwards trend in emissions.

Figure 8 presents a decomposition by activity, which shows that in a typical year around half of embodied emissions are attributable to material producing sectors. The proportions attributable to each activity remain similar throughout the analysis period: materials extraction, manufacturing and production (50.8-53.4%); construction activities (18.6-23.2%); transport of people, plant and materials (8.2-10.3%) and all other activities (16.1-19.8%). These results are consistent with past publications which demonstrated that the production of materials is responsible for the majority of embodied emissions from construction. This is hardly surprising as the construction industry consumes around 6 tonnes of materials every year

Figure 8: GHG emissions of the UK construction supply chain by activity



on behalf of each UK resident (Constructing Excellence, 2008). This implies that, if substantial reductions are to be made in embodied emissions from construction, much of the reductions must come from emissions attributable to materials. This necessitates either a reduction in the use of these materials or a reduction in the carbon intensity of their manufacturing processes. The opportunities for such reductions are explored in Section 3.5.

Figure 9 reveals that throughout the analysis period around half of total supply chain emissions (48-58% annually) occurred outside UK borders. Whilst in the years prior to the recession (2000-2007) there was a small rise in emissions attributable to imports from China, largely the emissions attributable to imports followed trends in total construction output, with the majority of emissions attributable to imports from the EU or Rest of World regions. This reflects a consistently strong dependence in recent decades upon imported materials (such as wood, steel and aluminium) which limits the scope of influence of UK territorial climate policies in achieving radical emissions reduction in the construction sector. Even combined UK and EU policies only govern around 65% of the current total. Consequently, current policies directed solely at UK or EU material producers are highly unlikely to achieve sufficient reductions in embodied emissions to achieve sector targets.

Figure 10 suggests that these emissions are incurred to provide a variety of structures, with the largest contributors being housing, offices and infrastructure. However, none of these individual categories is responsible for more than 18% of total emissions.

Figure 11 combines these perspectives, illustrating emissions by geographical origin, intermediate activity and end product. From such a diagram it is possible to

Figure 9: GHG emissions of the UK construction supply chain by region

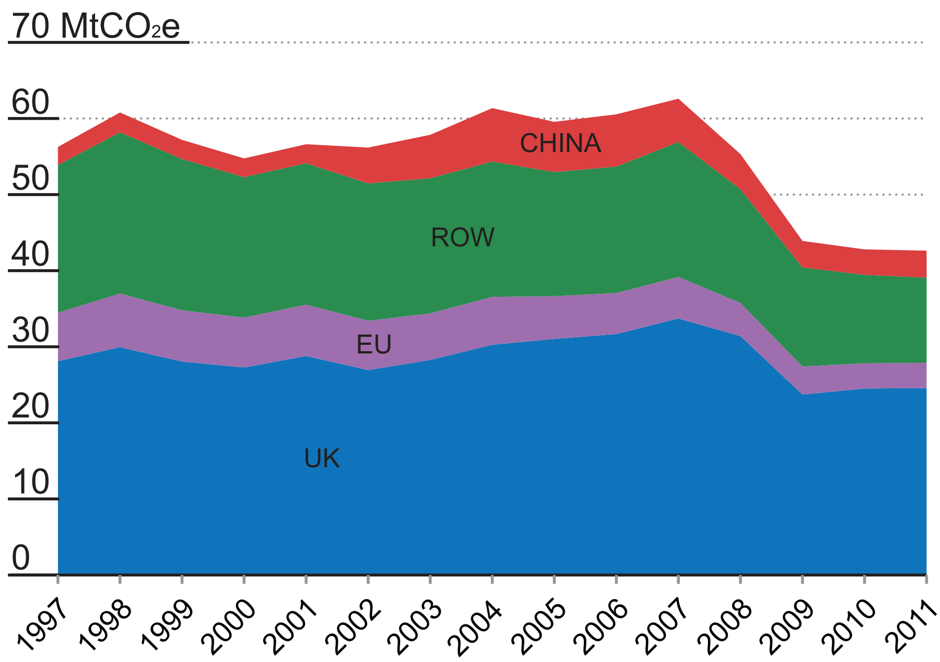


Figure 10: GHG emissions of the UK construction supply chain by end product

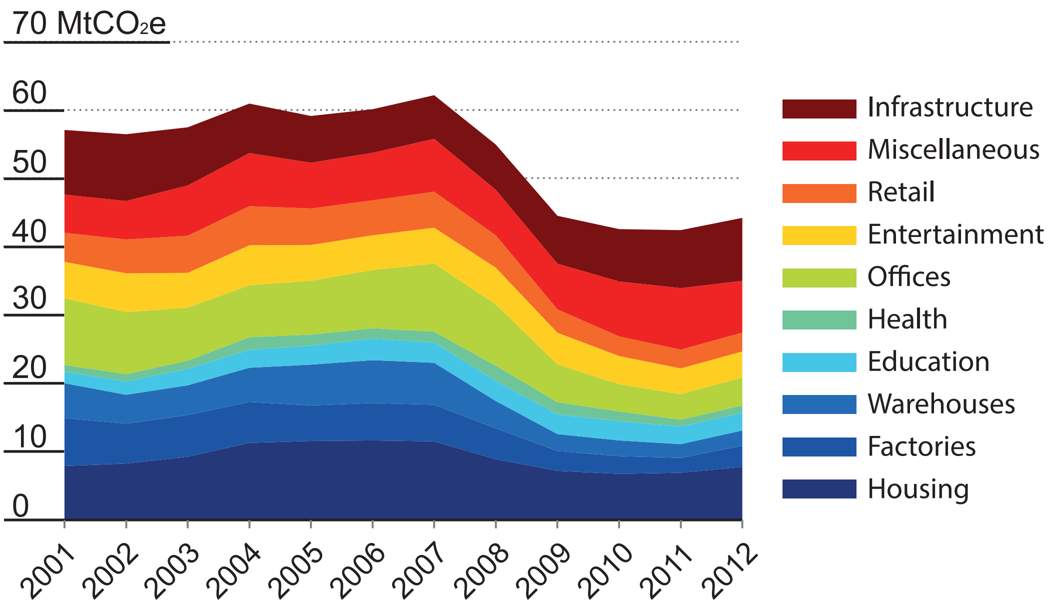
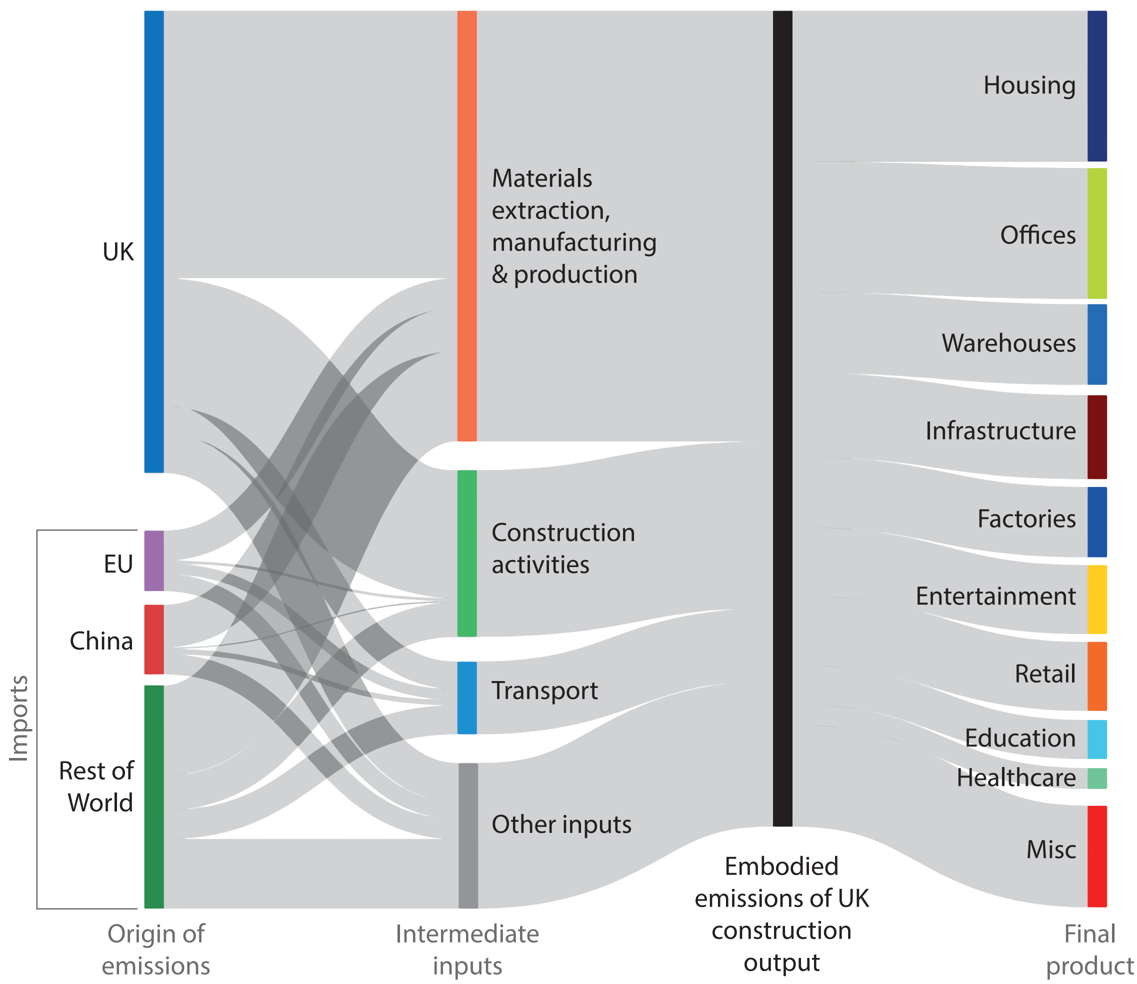


Figure 11: Embodied GHG emissions of UK construction sector in 2007



crudely evaluate the magnitude of emissions that could be influenced by strategies or policies addressing a particular activity or structure type. From this figure it is clear that, whilst policies addressed solely at UK material producers, transport of site workers, or at improving a particular type of structure can yield some savings, the largest leverage point resides in addressing total material demand. Indeed if reductions of the order suggested by the GCB Routemap are to be made then strategies must include a reduction in the emissions associated with building materials. Such reductions can be achieved either through improvements in production processes or reductions in demand. Given the significant proportion of imported materials, whose producers reside outside the influence of UK policy, it could be argued that the greatest opportunity for emissions reduction lies in reducing overall material demand. However, it is likely that sector emission reductions of the order of magnitude targeted will require both improvements from producers and reductions in total consumption. The following Section 3.5 explores the opportunities for reduction in emissions from material manufacture.

3.4.3 Comparison with bottom up approach

By way of comparison with this top-down approach, Doran (2014) compiled a bottom-up estimate of the embodied carbon in materials consumed by the UK construction sector using consumption volumes and product LCA data. Doran's approach painstakingly combined PRODCOM data for 185 construction categories with BRE's proprietary collection of product LCA data. An estimate was computed for 2011 of 20 $MtCO_2e$. This compares well with the top-down estimate for materials extraction, manufacturing and production of 22.5 $MtCO_2e$. The 12.5% difference in totals is likely accounted for by the differing system boundaries adopted in the MRIO approach compared with a series of process-based LCAs.

3.5 Exploring emission reduction opportunities within material production

Figure 11 demonstrates the need to reduce the embodied carbon of building materials through either improvements in production or reductions in demand. This section provides a brief overview of the growing significance of material consumption and summarises the opportunities for improvements in production.

It should be remembered that humanity had unwittingly been building sustainable structures for centuries before a modern conception of 'sustainability' was formed. However, the combined pressures of global population growth, economic development and increasing urban density dramatically increased demand for buildings and infrastructure throughout the last century. The corresponding global growth in construction activity has seen an unprecedented increase in the volume of building materials consumed. This growth has been coupled with a switch to engineered materials, including the increasing use of plastics, metals, concretes and composites and has, in large part, been powered by increasing fossil fuel consumption. These materials are now largely produced by bulk producers operating in highly mature and consolidated markets. This tale of staggering expansion and market globalisation is clearly illustrated by considering the consumption of two fundamental materials, steel and concrete.

Global growth in steel demand has largely been driven by China, where annual steel consumption grew from 240 to 700 million tonnes in a single decade between 2003-2013 (UK Steel, 2014b). During the same period Chinese cement production more than doubled and now exceeds 2.3 billion tonnes per annum (USGS, 2014). Consequently, Chinese cement production over the period 2011-2013 comfortably exceeded total cement production by the United States throughout the last century (Swanson, 2015). Total annual world production of cement is now in excess of 4 billion tonnes alongside steel production of over 1.6 billion tonnes. The dramatic acceleration of growth in global steel demand over recent decades is perhaps best illustrated by the following quote (UK Steel, 2011):

"Annual global production first exceeded 500 million tonnes in 1968 taking until 2004 for the 1,000 million tonne level to be reached. It has subsequently taken only seven years, a period including the worst economic crisis of recent times, for global crude steel production to pass 1,500 million tonnes."

This rapid growth in steel consumption is expected to continue, with authors suggesting global consumption of 1.7 times today's levels by 2050 (Allwood & Cullen, 2012 p. 292). Over the same period, global cement demand is projected to double.

In addition to the associated resource use, the manufacture of these two materials is responsible for a sizeable proportion of anthropogenic GHG emissions. In the UK, for example, the production of just steel and cement constitutes an estimated 44% of industrial carbon emissions (Allwood & Cullen, 2012 p. 13). Allwood and Cullen have argued that there are limited opportunities to reduce material production emissions as unavoidable emissions associated with key chemical processes, such as the calcination of limestone in cement manufacture and the reduction of iron ore by coke and oxygen in steel manufacture, now dominate (Allwood & Cullen, 2012 p. 99). They argue that, owing to the high costs of energy, material producers have long been strongly incentivised to improve production efficiencies. Consequently, many of the available improvements have been exploited and new production is slowly approaching practical thermodynamic limits (Allwood & Cullen, 2012 pp. 99–113). Let us interrogate this claim by considering carbon abatement opportunities within UK and global production of these two key materials, steel and concrete, in more detail.

3.5.1 Steel

The UK's steel requirement* has stabilised around 20 million tonnes per year since recovering from the recession (UK Steel, 2014b). The construction sector is responsible for more than a quarter of this consumption. Within the construction industry steel is used in a wide range of applications. Data detailing these end uses is hard to come by with the best estimates compiled by Moynihan and Allwood (2012). They suggest steel demand in the construction industry is allocated as in Table 5. Figures have been adapted to show percentages of overall steel consumption as the absolute values calculated by Moynihan and Allwood were only representative of 2006 output (which was significantly higher than current levels). In addition to the obviously significant volumes in the substructure and superstructure, Allwood and Moynihan suggest that as much as 20-35% can be used in non-structural applications in a 'typical' office building.

Just under half of UK steel demand is met by domestic supply, with the remainder imported. Steel is a global commodity, with around 30% of world steel output traded across an international border in 2010 (UK Steel, 2011). The international market is highly price sensitive and has seen dramatic changes in recent years. For instance, the four fold increase in Chinese steel production capacity over the past decade has started to influence the EU and UK markets (Pardo et al., 2012). As domestic growth and several Asian economies slowed in 2013-14, Chinese producers were left with an estimated excess capacity of some 200 million tonnes (roughly equivalent to total EU capacity) (UK Steel, 2014a). This resulted in a vast increase in Chinese exports, which are estimated to have trebled since 2009. Chinese exports of steel rebar in particular have grown from a negligible share of the UK market in January 2014 to a 37% share by year end (UK Steel, 2014a). This rebalancing of the global market is set to lead to a change in associated emissions, with significant variations in the carbon intensity of production between the major steel producing nations. Though there are wide variations in the estimated carbon intensity of Chinese steel production - as summarised by Li et al. (2016) - when compared across the same system boundaries, Chinese production appears to be more carbon-intensive than other key global producers (Hasanbeigi et al., 2016). This is particularly the case for steel produced from the EAF route, where Chinese production is dependent on a more carbon-intensive electricity supply. This is a particular concern for key products entering the UK market, such as rebar.

The UK domestic market is dominated by five large international steelmakers, the largest of which, Tata Steel Europe, had a 45% market share in 2013 (WSP et al., 2015b). Following significant revenue contraction during the recession, these companies are primarily focussing on cost savings and business continuity.

*This steel requirement represents steel mill products from UK mills, imported steel mill products and steel contained in imported goods.

Although two of the five companies have corporate climate change strategies that target a reduction in emissions, decarbonisation and energy efficiency are not currently considered as high-priority business goals. The industry competes in a volatile international market, primarily on the basis of cost, with minimal market for low carbon products. Consequently, the long term survival of the UK industry is primarily dependent upon the ability to access growing international markets, such as India, and to obtain reliable low cost sources of key materials and energy. The mothballing of Tata Steel Teesside in 2009, followed by a decline in demand, and close to record level prices in iron ore and coking coal in 2011, led to UK steel production reaching its lowest output since 1934 in 2012 (UK Steel, 2014b). Output recovered somewhat with the re-commissioning of the Teesside plant in 2013 and a growth in demand from the construction and automotive sectors. However, increasing competition from Chinese imports resulted in a series of high profile job losses throughout 2015 and continues to threaten the long-term viability of the UK industry. The industry's weak financial position has limited the capital available for energy efficiency investments and large scale demonstration projects.

Just seven sites are responsible for 90% of the UK's domestic emissions from steel manufacture. The majority of plant at these sites is continuously upgraded or retrofitted rather than replaced, and will likely be exposed to only one or two further investment cycles between now and 2050 (WSP et al., 2015b). If decarbonisation projects are to garner investment in this period they must offer better financial returns than competing projects proposed within the international business groups; and be presented within a broader narrative of a sustainable financial future for the UK steel industry.

Table 5: Allocation of steel products by application in UK construction (based on Moynihan & Allwood, 2012). All figures expressed as % of total steel consumption.

Sector	Sections	Rebar	Sheet	Rail	Tubes	**Total**
Buildings	27.6	13.8	24.1	0	8.6	**74.1**
Industrial	13.8	0	12.1	0	3.4	**31**
Commercial	5.2	3.4	3.4	0	1.7	**13.8**
Offices	3.4	1.7	3.4	0	1.7	**10.3**
Public	1.7	5.2	1.7	0	0	**8.6**
Residential	1.7	3.4	1.7	0	0	**6.9**
Other	1.7	0	1.7	0	0	**3.4**
Infrastructure	1.7	12.1	1.7	3.4	6.9	**24.1**
Utilities	0	6.9	0	0	5.2	**13.8**
Rail	0	0	0	3.4	0	**3.4**
Bridges	0	0	0	0	0	**1.7**
Other	0	3.4	0	0	1.7	**5.2**
Total	**29.3**	**25.9**	**25.9**	**3.4**	**15.5**	**100**

Crude steel can be produced by either the primary route, where iron ore is reduced to iron in a blast furnace (BF) then combined with small amounts of steel scrap (up to 30% (WSP et al., 2015b)) in a Basic Oxygen Furnace (BOF), or by the secondary route, melting steel scrap in an Electric Arc Furnace (EAF). In 2012, 79% of UK crude steel production was from the primary BF-BOF route and the energy intensity of UK BF-BOF production was 17.1 GJ/t crude steel (UK Steel, 2014b). This was better than the EU average of 21 GJ/t (Pardo et al., 2012) but offers some scope for improvement compared with a world best practice of 14.8 GJ/t (Worrell et al., 2008). Meanwhile, the energy intensity of UK EAF represents current best practice at 2.5 GJ/t (WSP et al., 2015b). These figures represent substantial improvements over recent decades from an average energy intensity for UK production of 31.7 GJ/t in 1973 (UK Steel, 2012). However, most of this reduction was achieved by the early 1990s through the adoption of technologies that are today considered standard for any state-of-the-art plant. Since then minimal reductions have been seen in intensity.

The lowest practically achievable level of carbon emissions for hot rolled virgin steel (produced by BF-BOF) has been estimated at 1.352 tCO_2/t (Fruehan et al., 2000). This figure stems predominantly from the process emissions needed in the reduction of iron ore by coke and oxygen in the BF. However, in spite of this, steel producers commonly quote product carbon footprints below this level. For example, Tata Steel have attributed current steel construction products in the UK with carbon footprints of 0.76-1.35 tCO_2/t depending on section type (Tata Steel, 2012). To achieve such a low figure, it requires that a number of assumptions be made. First, the adoption of a closed loop recycling system, as advocated by the World Steel Association (World Steel Association, 2011). Secondly, that the benefits of future recycling and offsetting of further virgin production be included within the headline product footprint. Both of these assumptions can be questioned.

First, though a significant proportion of steel is recycled, downcycled or re-used, the UK system could not accurately be portrayed as a fully closed loop. Recent surveys of UK demolition contractors suggest that 91% of construction steel is recycled with a further 5% re-used (Sansom & Avery, 2014). This represents only a marginal improvement on 2000 levels when 85% was recycled and 8% re-used. Though the surveys highlight potential for further steel re-use - avoiding the need for energy-intensive re-melting - they do not suggest that full recycling is imminently achievable. However, accurately reflecting these figures in an LCA of UK steel would only result in minor differences to the headline footprint. The more critical assumption is the benefits attributed to future recycling.

Though likely, it cannot be guaranteed that future recycling of any steel product will be achieved or that this recycling will offset further virgin steel production. The industry's default approach inherently assumes that at the end of a steel construction product's useful life that future steel production technology will be of a similar carbon intensity to current technology, and that there will be sufficient scrap demand to exhaust supply. This approach also implicitly assumes that the notional future carbon savings achieved by preventing additional production are of equivalent benefit to carbon savings incurred in the present day. Given the significant uncertainties in prediction of product end-of-life scenarios and associated benefits, it is best practice to state such information separately within any carbon reporting (e.g. within module D of an EPD). However, the industry commonly promotes only the most flattering headline figure. For example, the carbon footprint of UK average rebar is commonly quoted as 0.82 tCO_2/t (Tata Steel & BCSA, 2012), even though a recent EPD provides a mean life cycle global warming potential of 1.33 tCO_2/t steel when module D benefits are excluded (BRE & UK CARES, 2016).

In 2013 the EC launched an action plan for a competitive and sustainable steel industry in Europe (EC, 2013). The plan was principally concerned with reversing the decline of the European industry which has suffered from simultaneous effects of high energy prices, low demand and overcapacity in a globalised market. Research commissioned prior to the plan found that uptake of all best available technologies under currently acceptable payback periods across all EU plant between 2010-2020 would only yield a 2.8% reduction in CO_2 emissions (Pardo et al., 2012). Consequently, the EC stated that "*most modern installations in the EU steel industry are close to the limits of what current technologies can do, and the steel industry will struggle to achieve further significant CO_2 emission reduction without the introduction of breakthrough technologies*."

In 2015 a roadmap for the UK iron and steel sector was published as part of a series of eight Industrial Decarbonisation & Energy Efficiency Roadmaps for energy intensive industries prepared for DECC & BIS (WSP et al., 2015b). The roadmap authors projected business-as-usual carbon reductions of 15% on 2012 levels by 2050 through the reduction of yield losses; exploitation of steam or power production systems upgrades; heat recovery and re-use and grid decarbonisation. Extended deployment of the available technology options, requiring investment of the order of £400 million, could see this reduction extend up to a limit of 28%. Further reductions beyond this point would require the introduction of CCS. Additional reductions could be made if an increased proportion of steel was produced in EAF but the BF-BOF/EAF split has remained relatively constant in the UK and EU over the past decade (Egenhofer et al., 2013). Such a switch would increase dependence on scrap availability in a global market where scrap demand is *"getting very close to total available scrap supply"* (The Carbon Trust, 2011). A switch to EAF would also imply a switch to electricity, which, with the UK's perceived higher relative costs and competitiveness issues, appears an unlikely option. This suggests that there remains little scope in the short to medium term for dramatic reductions in the emissions attributable to UK or European steel production.

In the long term, research is on-going into breakthrough technologies through large consortium funded schemes such as ULCOS (Ultra-Low CO_2 Steelmaking). The four main ULCOS technologies under investigation are blast furnace with top-gas recycling (TGR-BF); a new smelting reduction process (HIsarna); advanced direct reduction (ULCORED); and electrolysis of iron ore (through two processes: ULCOWIN and ULCOLYSIS). The application of these technologies alongside CCS is a principal consideration of the scheme. Indeed, the first two technologies can only deliver the scheme's targetted 50% reduction in carbon emissions per tonne of steel if deployed alongside CCS. The scheme is also funding initial research into hydrogen-based steelmaking and the use of biomass as a reducing agent. A recent overview of project progress across all technologies is provided by Abdul Quader et al. (2016). Three of the four principal technologies are now being tested in pilot plants; whilst the fourth requires "*several hundred million euros*" for testing on a commercial scale furnace. The EC estimates that the full ULCOS-related spectrum of demonstration experiments would cost in excess of €500 million (EC, 2013). None of the four technologies have yet achieved commercial deployment, with full-scale testing unlikely until the 2020s. Even if some commercial deployment can be achieved in the 2030s, it is unlikely that this will be on aging UK plants. This is largely a result of a UK business environment that is *"not conducive to large-scale demonstration projects"*, with *"limited capital"*, where *"decarbonisation is not a strategic issue"* and investment in new plants is highly unlikely (WSP et al., 2015b).

Consequently, even if technological development proceeds swiftly, it is unlikely that substantial reductions (>20%) in the carbon footprint of steel produced or consumed within the UK will be achieved within the coming decades. In fact with minimal scope for reductions from EU imports and likely increases in overall emissions from imports due to growing use of Chinese steel, any reductions in domestic emissions in the coming years may be negated by growing emissions from imports.

3.5.2 Concrete

With a global consumption rate approaching 25 gigatonnes per year, concrete is second only to water in total volume consumed annually by society (Petek Gursel et al., 2014). Indeed, it has been suggested that twice as much concrete is used in global construction than the total of all other building materials (University of Liverpool, 2012). Similarly, it has been estimated that the volume of concrete consumed in the UK comfortably exceeds the volume of all other construction materials combined (IEA, 2009). Whilst aggregates make up 60-75% of concrete by volume, their extraction and processing are responsible for relatively low levels of carbon emissions, with the majority of concrete's carbon footprint attributable to the production of cement. The cement industry is widely accredited with 5-7% of global CO_2 emissions (Benhelal et al., 2013; Hasanbeigi et al., 2012; Shi et al., 2011). In the UK, domestic production of cement is estimated to constitute 2% of the UK's total carbon footprint (MPA, 2012).

Production of the UK's 2013 concrete mix emitted 85.2 kgCO_2/t for mass concrete, and 92.6 kgCO_2/t for reinforced concrete (with reinforcement contributing around 8% of total emissions) (MPA, 2014a). This figure shows an almost negligible improvement from the baseline of 87.5 kgCO_2/t for mass concrete established when the UK industry launched its most recent sustainability strategy in 2008. The marginal improvements observed can largely be attributed to a small reduction in waste and the increased diversion of waste streams for use as a fuel source. During this time the use of additional cementitious materials has remained fairly constant, representing 26.4-30.6% of total cementitious materials. The use of recycled or secondary aggregates has increased somewhat from 5.3 to 6.9% of total aggregate use. The emissions from transport have remained, on average around 8 kgCO_2/t, though this figure varies significantly from project to project and product to product. The average delivery distance for all concrete is 41km. This figure has increased slightly in recent years but the increased travel distance has been offset by greater use of more carbon efficient rail transport. Whilst some limited scope remains for further improvements in transport of ready-mix and aggregates, the principal source of emissions in UK concrete manufacture remains the production of cement.

Total UK consumption of cementitious materials was some 12.433 Mt in 2014 (MPA, 2015a). This comprised cement consumption of some 10.568 Mt, of which 8.751 Mt (83%) was produced domestically and 1.817 Mt (17%) was imported. Other cementitious materials such as fly ash and GGBS totalled an additional 1.864 Mt. This represents a recovery in total consumption from a recession low of 10.338 Mt of cementitious materials but remains well below the 2007 peak of 15.783 Mt.

The cement industry in the UK is dominated by four multinational manufacturers (CEMEX, Hanson, Lafarge Tarmac and Hope Construction Materials) with a total turnover of £426 million in 2012 (WSP et al., 2015a). All four manufacturers have climate change strategies and KPIs in place and view decarbonisation as an important strategic priority. However, all operate within a global market place and experience high levels of internal competition for investment in new plant and equipment. Most investments in the sector are usually expected to pay back within three years and require group level approval. Consequently, all firms have established pipelines of energy reduction projects that await funding. Most of these projects represent incremental changes as the majority of ideas with high impacts and lower risks have already been deployed by the sector throughout the past decade (WSP et al., 2015a).

The principal piece of equipment in a cement production facility is the kiln, which accounts for around three quarters of energy use in a typical plant. Kilns typically have operational lifespans of 30-40 years and are rarely out of operation owing to the high financial losses from down time. In the UK market, modifications and partial rebuilds are more frequent than complete new build and, with the current generation of UK kilns all built or modified within the last 15 years, only one replacement cycle is likely between now and 2050. This significantly restricts opportunities for the introduction of any large scale disruptive technologies in the sector. Any such technologies would need to be market ready in the next decade given the typical seven years taken to plan and build new plants. Consequently, further equipment investments are only anticipated to yield incremental energy and carbon savings.

The UK industry has already changed significantly across the last decade reducing emissions by 24.9% from 924 $kgCO_2$/t of Portland Cement Equivalent in 1998 to 694 $kgCO_2$/t in 2013 (MPA, 2014b). Around 474 $kgCO_2$/t (68%) of these remaining emissions comes from the essential calcination of raw materials (MPA, 2010). By 2010, this reduction had already exceeded the industry's 2015 target set by the Environment Agency of 775 $kgCO_2$/t. In 2014 the sector's principal trade association, the Mineral Products Association (MPA), were issued with the first EPD for UK Average Portland Cement Production (distinct from the industry preferred unit - Portland Cement Equivalent), quoting a verified global warming potential of 846 $kgCO_2e$/t (MPA, 2014c). The reductions observed in the last decade were principally achieved by investment in new plant and the adoption of waste-derived fuels at five of the UK's twelve production sites. These fuels are a mix of solid recovered waste (such as waste carpet), recycled liquid fuel, tyre chips, meat and bone meal and processed sewage pellets. Indeed, the UK industry now consumes over 1.5 million tonnes of waste and by-products as fuels and raw materials annually (MPA, 2014b). The proportion of fuel comprising waste material has reached 44%, rising from 6% in 1998. There remains some scope for further increase in this share, though, it has been suggested that the upper limit for alternative fuel use is somewhere between 60% and 80% (due to the need to maintain consistent heat patterns) (WSP et al., 2015a). The evolving market for alternative fuels also poses a barrier to further expansion, with many formerly cheap wastes rising sharply in price. The introduction of policies such as the Renewable Heat Incentive has increased competition for biomass and provided an incentive to move biomass use from cement kilns to potentially less efficient uses.

The industry, through the former British Cement Association, adopted its first Carbon Strategy in 2005 which focussed on expanding cementitious additions to 8% and delivering 15% alternative waste derived fuel use by 2010. This was followed in 2013 by the launch of the MPA's 2050 carbon reduction strategy which targets a headline 81% reduction on 1990 carbon emission levels by 2050 (MPA, 2013). However, as shown above, much of this reduction has already been achieved (with a 55% absolute reduction from 1990 levels by 2011). Much of the remaining reduction hinges upon potential installation of CCS, without which the target is reduced to 62%. Assuming no CCS, this represents a targeted reduction of only 15% on 2011 levels by 2050. This reflects the limited scope for improving production efficiencies and the predominant share of emissions from unavoidable processes.

The most recent roadmap for the UK sector anticipates even more limited reduction opportunities, projecting business-as-usual reductions of 11.9% in carbon intensity by 2050 (against a 2012 baseline), with three quarters of these reductions attributable to projected grid decarbonisation (WSP et al., 2015a). Even scenarios combining maximum plausible uptake of cementitious substitutes and alternative raw materials with substantial increases in the use of alternative cements and biomass fuels, were projected to yield an overall reduction of only 20% on 2012 levels. Once again, any substantial reductions were deemed to hinge upon the introduction of CCS. However, the industry expectation is that fitting CCS would double the capital cost and physical size of a new plant and increase energy requirements by 50% (WSP et al., 2015a). Individual cement plants in the UK are not considered to be of a sufficient scale to justify their own CO_2 pipeline and storage infrastructure. Consequently, without a significant shift in global prices, the introduction of government incentives, and collaboration or clustering with other CO_2 capturing or consuming industries it is unlikely that a robust business case can be made for CCS. In the meantime it remains "*extremely unlikely*" that any of the UK companies would be able to gain management or shareholder buy-in even for demonstration projects (WSP et al., 2015a). The lack of a stable and profitable business environment; combined with an unpredictable regulatory environment; and concerns around a loss of international competitiveness are already preventing capital investment in less onerous technologies.

On a global scale, many of the cost effective mitigation options have already been exploited, with emissions per tonne of cementitious product reducing from 761 $kgCO_2$ in 1990 to 638 $kgCO_2$ in 2012 (Cement Sustainability Initiative, 2012). This has largely been achieved through improved thermal and electrical efficiency; use of alternative fuels; and increased clinker substitution. The IEA in collaboration with the WBCSD's Cement Sustainability Initiative published a 2050 Technology Roadmap for the global cement sector in 2009 exploring the potential for further reductions (IEA, 2009). The report suggested that global production could be within the range 352-636 kgCO_2/t of cement by 2050. However, the lower end of this estimate hinged upon the deployment of up to 400 commercial plants fitted with CCS, the earliest of which would be installed by 2025. At the time of writing CCS technology has not been fitted on any commercial material production facility in the world (Li et al., 2013).

As a consequence of the prevailing business environment, and with limited scope for technological interventions, it is unlikely that substantial reductions (>15%) in emissions from UK cement manufacture or imports will be achieved within the coming decades. Other processes involved in concrete manufacture, such as the transport of aggregates, offer equally limited scope for improvement.

3.6 Reducing demand for carbon-intensive materials

The preceding section highlighted the limited anticipated improvements in the carbon intensity of two key materials: steel and concrete. Similar conclusions can be drawn about other materials such as plastics, zinc and copper. Owing to the high costs of energy, material producers have long been strongly incentivised to improve production efficiencies. Consequently, the majority of available improvements have been exploited and limited scope remains for further improvement. Emissions associated with key chemical processes now dominate. Without CCS these process emissions are unlikely to be reduced. Widespread CCS is unlikely to occur within the timescale required to contribute to the construction sector's 2025 emission reduction targets. Consequently, short to medium term emission reductions of the order of magnitude desired are unlikely to be met through improvements in material production alone. If substantial reductions are to be made in embodied emissions, then reducing demand for these carbon-intensive materials must play a significant role.

This argument is supported by other authors, including notable advocates of 'material efficiency' – a catch all term for a collection of strategies that provide equivalent material services with less material production and processing (Allwood et al., 2011). For example, Allwood argues that "*to meet the emissions targets set into UK law, UK consumption of steel must be reduced to 30 per cent of present levels by 2050*", even if optimistic assumptions are made about improved production efficiencies (Allwood, 2013). In general, material efficiency encompasses six principal strategies: light-weight design; reducing yield losses; diverting manufacturing scrap; re-using components; longer-life products; and more intense use (Allwood et al., 2013). In the construction sector material efficiency is more specifically defined as "*the* *process of undertaking a building project to enable the most efficient use of materials over the lifecycle of the building and its components*" (BSI, 2013). This includes adopting good practice to design out waste (WRAP, 2009b); technical solutions such as the use of variable depth structural members (Carruth & Allwood, 2012) and building level structural optimisation (Moynihan & Allwood, 2014); and maximising the useful life of materials by extending the life of existing structures and designing new structures to be adaptable and easy to deconstruct (Densley Tingley, 2012). In addition to the options considered by advocates of material efficiency; there are also many opportunities to increase the use of low carbon building materials and products (Cabeza et al., 2013). A variety of alternative materials are available, including: materials derived from naturally occurring substances; materials that incorporate wastes or recycled content; and construction products that have been optimised through novel production techniques. Chapter 4 considers this range of options for reducing demand for carbon-intensive materials in further detail.

3.7 Summary and discussion

When developing a long term plan for deep national carbon reductions, it is essential to understand the aggregate impacts and mitigation opportunities within all major sectors of an economy. Yet, despite its considerable size and influence, it is impossible to swiftly distinguish the aggregate impacts of the construction sector within UK national GHG emissions accounts. As revealed in the initial literature review, prior attempts to estimate the magnitude and distribution of supply chain emissions have depended upon outdated and incomplete data and a number of simplistic assumptions. Consequently, prior estimates have underestimated the impacts of current and projected UK construction activity. A more detailed understanding of the magnitude of these impacts, and their distribution along supply chains, is essential in identifying the intervention points that may yield the greatest carbon reductions.

This chapter has presented a new best estimate to date of the embodied carbon associated with the UK construction supply chain. Results have been presented according to spatial origin, intermediate activity and final product. This estimate suggests that prior to the recession construction supply chain emissions were broadly equivalent to tailpipe carbon emissions from all cars in the UK. Even at post recessionary levels of construction, embodied emissions were higher than the combined 2050 target for embodied and operational emissions of 42 MtCO2e suggested in the GCB Routemap. Therefore embodied emission reductions in excess of the 39% already suggested by the GCB will be necessary if an 80% reduction in total sector emissions is to be achieved. The analysis suggests that this would require a substantial overall reduction in material use facilitated by the substitution of current building products for low carbon alternatives and the adoption of strategies for greater material efficiency. A wide variety of options of this sort are detailed in the next chapter. The barriers preventing greater uptake of these options are also investigated in Chapter 5. However, as discussed in Chapter 2, there are few policies driving embodied carbon reduction. To date, the development of climate mitigation strategies and policy has largely been framed by the sectors used within territorial emissions accounts. This may be one reason why policy levers within cross-sector activities, such as construction, have received less attention. Given the sheer magnitude of supply chain emissions, it is reasonable to argue that construction should receive comparable attention to other key economic sectors when formulating climate mitigation strategies and identifying policy responses.

In the absence of such drivers, it remains unclear how the sum of individual selections made by design teams based on limited information could yield savings in capital carbon emissions of the order required. A dearth of quantitative evidence exists, not only in assessing the environmental impacts of individual construction materials and products, but in evaluating the cumulative sector wide changes that may be necessary to meet emission reduction targets (Green Construction Board 2013b p. 4; HM Government 2010b pp. 27–28; Thomas et al. 2012). For example, further research is required to develop a means for translating sector wide reduction targets into targets for specific structure types and individual projects. Whilst the WRAP Embodied Carbon Database has begun to facilitate relative project level benchmarking amongst design teams, it does not allow system or component level benchmarking, nor does it indicate the adequacy of a design's absolute performance in the context of UK climate mitigation strategies. In the long term it is essential that a link is formed between sector level reduction targets and the tangible project level benchmarks utilised by design teams. The challenges involved in establishing such a link are explored in Chapter 6.

It is also important to remember that the current embodied emissions total represents the sector during a period of historically low construction output. The projected growth in housing and infrastructure in particular could significantly expand this total and potentially undermine the strategic targets. Consequently, there is good reason to investigate the scope for a demand side response. To date, the responsibility for embodied carbon reduction has largely been passed down the supply chain to material producers. However, Section 3.5 demonstrated that there is limited scope for key material producers to make sufficient carbon reductions owing to a combination of physical, practical and economic limits to domestic manufacturing and the UK's dependence upon imports. This imbalanced focus upon supply-side responses, neglects the many potential co-benefits of a more balanced approach incorporating demand-side responses. Chapter 6 considers the implications of future demand for building stock on project level embodied carbon targets and explores the potential role for demand reduction.

4. Options for reducing the use of construction materials with carbon-intensive supply chains

We are stuck with technology when what we really want is just stuff that works

Douglas Adams

4.1 Introduction

The analysis presented in the previous chapter showed that the majority of embodied emissions attributable to UK construction industry supply chains are from materials extraction, manufacture and production. Given the limited scope for emissions reduction in the manufacture of key stock materials, meeting strategic carbon reduction targets will necessitate a reduction in the aggregate use of materials with carbon-intensive supply chains. This chapter provides a review of alternative materials, design strategies and business models that could support such a reduction. Subsequent discussion highlights their potential scope for application within the UK.

Section 4.2 introduces the research objectives, boundaries and methodologies applied in the remainder of the chapter. Sections 4.3-4.5 highlight some design strategies, alternative materials and business models that could be employed to minimise the use of carbon-intensive materials. Section 4.6 collates the options and discusses common features. Section 4.7 concludes the chapter with a brief summary.

4.2 Research methodology, objectives and boundaries

The principal objective of this chapter is to provide a broad appraisal of options that could deliver substantial reductions in the use of construction materials with carbon-intensive supply chains. The appraisal of options is formed through a systematic process of gathering and reviewing the available literature. Whilst not constituting a formal systematic review, as typically conducted in medical research, the review attempts to identify, appraise, select and synthesize available research on the topic within a pre-defined framework according to a review protocol. By this means an evidence base was gathered from an extensive literature search of academic publications, supplemented by data and publications from trade bodies and other non-academic sources. This evidence base was filtered using relevance ratings prior to review and the key features of each low carbon alternative, and the barriers to their adoption, were extracted and synthesized.

The review considers only options that are suitable for application on UK construction projects and reduce supply chain carbon emissions either within or outside UK borders by reducing total material consumption or displacing the conventional use of a more carbon-intensive material. The review principally considers applications within buildings rather than infrastructure works. The review also focusses specifically on structural and functional elements of the building fabric and does not consider building services, adhesives, fixtures and finishes. Though in many building studies a notable proportion of total life cycle emissions are attributable to non-structural materials (Medas et al., 2015), it seems self-evident that where emissions reduction is considered a key criterion at the design stage, services and finishes with minimal environmental impacts should be preferred by designers and specifiers. Given the short-order emission reductions necessitated by climate targets, the review is primarily concerned with solutions that can be applied in the short-medium term. Although, it is important to stress that the impact of any particular solution is best assessed over the full lifetime of each building. Therefore, the review considers the scope for reduced impacts over the lifetime of new structures that will be constructed prior to 2050.

The review is guided by five research questions:

1. What alternative materials, technologies or practices could reduce demand for carbon-intensive materials in the UK construction sector?
2. Do these alternative materials, technologies and practices provide comparable physical performance to the materials they displace? Or, in cases of alternatives with lower comparative physical performance, do they provide sufficient performance to meet the functions required of the materials they displace?
3. Would use of these materials, technologies or practices be acceptable in social and economic terms?
4. Does a sufficient supply chain exist, or could a supply chain be readily formed, to achieve deployment of these options within the relevant timeframe?
5. At what scale could each alternative material, technology or practice be practically applied within the UK sector?

An initial literature search was conducted using 115 search terms outlined in Appendix B. The initial searches in Science Direct, Compendex, Inspec and Google Scholar returned 5264 results from which 1154 publications were extracted. Further evidence was added from citation trails and from consulting the work of relevant institutions in each field. In total, 1494 pieces of evidence were gathered for consideration. This high volume of results was filtered by applying an approach similar to that adopted by UKERC in their Technology and Policy Assessment Reports (UKERC, 2012). All pieces of evidence were assigned a relevance rating as outlined in

Table 6. Detailed attention was paid to those documents of high relevance (rated 1 or 2), with limited use made of evidence rated 3 or 4. This evidence base was used to assess options against a set of common assessment criteria.

The common assessment criteria included: physical performance, environmental impacts, economic competitiveness, social acceptability, ease of implementation, sufficiency of supply chains, and readiness for widespread deployment (see Appendix B for further details). All options were assessed against these criteria and rough review documents were compiled for each of the most promising options. These review documents constituted an evidence base that informed the remainder of the project work.

It should be noted that the volume of literature forming this evidence base was not evenly distributed across the range of options. As noted by Ledbetter et al. (2007) the preponderance of research publications received by academic journals focus upon concrete, cement, masonry and bituminous materials. Other materials with less developed industries and research networks are represented by fewer publications. It is also apparent that options developed in academia claim a greater number of publications than those developed in industry. This is hardly surprising, owing to the academic imperative for publication and the desire of commercial manufacturers to protect intellectual property. The inclusion of a substantial body of grey literature goes some way towards counterbalancing this effect. The literature also displays a strong focus on technical aspects of production or performance, with a minimum of publications focussing on aspects influencing selection, installation or public acceptance. The use of examples or case studies is also significantly more common within the grey literature than the peer-reviewed literature.

When providing a concise and accessible overview of the literature it is not possible to expound upon all assessment criteria at length for the broad range of alternative materials, design strategies and business models encountered. Thus the following sections consist of a brief summary of key options drawn from a broader set of review documents. Where other authors have published overviews these are noted, and the reader is encouraged to consult these for further information. A full list of options can be found in Table 10 on page 125.

Table 6: Relevance ratings used to filter results of literature search

Relevance rating	Description of evidence
1	Evidence clearly deals with one or more key aspects of research questions
2	Evidence is relevant but presented in a way that could preclude direct comparison with other results
3	Evidence is of limited relevance
4	Evidence deemed not of relevance upon closer inspection

4.3 Design strategies

Sustainable designs are most commonly identified as those that are durable, adaptable, and efficient in their use of materials. As Mackay points out, "*the most valuable buildings are those that are adaptable during their life, enabling effective changes of use to take place, but are also easily dismantled into components that can be recycled or reused with minimal energy expenditure*" (Ledbetter et al., 2007). Often there can be trade-offs in achieving these common goals of material efficiency, durability, adaptability and recoverability (Kestner & Webster, 2010). However, the best designs ensure a balance between all these interests.

Extensive guidance and recommendations for best design practice are set out in BS 8895: Designing for material efficiency in building projects. Parts 1 and 2 (BSI, 2013; BSI, 2015) provide codes of practice for practitioners involved in RIBA work stages 0-3 (Strategic Definition through to Developed Design). Parts 3 and 4 were under preparation at the time of writing but are proposed as codes of practice for 'Technical Design' and 'Operation, refurbishment and end of life'. BS 8895 recognises twin material sustainability goals of minimizing environmental damage through specification of materials with low environmental impacts measured over the life cycle of the building and ensuring efficient use of materials. The efficient use of materials is achieved through optimizing material use and minimizing potential waste; utilizing materials recovered on site or locally; and procuring products containing higher than standard levels of recycled content. This includes a focus on implementing the common waste hierarchy (Reduce, Reuse, Recycle, Recover, Dispose) and WRAP's five principles for designing out waste (WRAP, 2009b). These principles are: design for reuse and recovery; design for off-site construction; design for materials optimization; design for waste efficient procurement; and design for deconstruction and flexibility. Part 1 of the standard sets out roles and responsibilities for the respective project participants and a process by which material efficiency opportunities should be identified, investigated and implemented, including incorporation of material efficiency objectives into the project brief. Part 2 includes further guidance, such as material efficiency checklists, intended to ensure the material efficiency actions identified and reviewed at the concept design stage are incorporated into the developed design stage. Whilst BS 8895 offers detailed guidance on the project process, it only offers general guidance on the design options under consideration (see Table 7). Consequently, the subsequent sections review some of the principal design options for achieving these sustainability goals, and assess the scope for greater material efficiency in construction. These sections in turn address options for reducing extraneous material use, designing for longevity, and designing for deconstruction in new buildings.

Table 7: BS 8895:2 Design and project delivery considerations to optimize material efficiency (BSI, 2015)

Areas	Examples
Project delivery approach	Consider options to demolish, refurbish, or new build. Undertake pre-demolition/strip-out fit out audit, if the project involves refurbishment and/or demolition. Consider alternative procurement models that deliver improved material efficiency, particularly over the building's lifecycle.
Design optimisation	Consider the design in the context of using fewer materials and/or materials better suited to their functional need. Consider prefabricated solutions using modern methods of construction (MMC) or off-site solutions. Specify the modular/standard size supplies and prefabricated materials. Consider designs with a simple form, layout, mass, sizing and orientation, etc.
Outline material specification	Specify reclaimed materials and products with recycled content. Maximize the durability and service life of building elements and services in relation to their replacement cycle. Specify materials having resources with no scarcity and with source security. Use specifications to avoid materials that are potentially wasteful, hazardous or have potential issues at end of life. Consider materials and products which have their packaging optimized. Specify materials with low volatile organic compound (VOC) content to create a healthy indoor environment. Propose components/materials that can be reused or recycled after deconstruction

4.3.1 Designing for high utilization of components

It is commonly argued that in many structures up to a third of the material used can be excess to design requirements (Allwood & Cullen, 2012; WRAP, 2009c). This is usually a result of either:

» rationalisation – a process whereby a variety of component sizes are simplified to a smaller set of sizes to simplify site work.

» cheaper manufacture of standard parts – many of the processes whereby typical components, such as I-beams, are fabricated are cheaper for members with a constant section along their length. It is also often cheaper to purchase the most readily available off-the-shelf sizes and to ensure a limited range of sizes across a project.

» over-specified components being copied across or between projects to minimise design time.

» higher specifications required for the construction phase that are surplus to in-use requirements.

» overly conservative regulatory requirements.

Over recent decades terms such as 'lightweighting' and 'member optimisation' have arisen to describe fields that essentially endeavour to minimise this excess through improved design or manufacture. For instance, computational optimisation has helped reduce the weight, cost and emissions associated with many structures, and continues to provide further scope for improvements through application of novel evolutionary optimization methods (Camp & Huq, 2013). The rise of BIM and holistic evaluation tools for estimating the embodied emissions associated with an entire structure, will allow for greater optimisation, for example through the selective use of higher grades of concrete and steel (Habert et al., 2012). This can significantly reduce the required volume and self-weight of a structure, in turn reducing the size of foundations and leading to overall reductions in the associated environmental impacts.

4.3.1.1 Novel manufacturing technologies

Novel manufacturing technologies have also given rise to a range of products that reduce excess material use. For instance, the use of cellular and open web-joist beams is now commonplace, as is the use of precast and hollowcore floor slabs and mesh reinforcement. There are further options to optimise these elements through the greater use of products such as variable cross-section beams and computationally optimised roll-out reinforcement carpets (e.g. BAMTEC and ROLLMAT). Steel beams are produced with a uniform cross-section for ease of manufacturing, not to meet a structural need, and the use of members with varying cross-sections could significantly reduce material requirements (Carruth et al., 2011). Current methods of manufacture are prohibitively expensive; however, cheaper production methods are in development (Carruth & Allwood, 2012). Computationally optimised roll-out reinforcement carpets, in addition to eliminating rationalisation waste, offer practical advantages, such as quicker installation without skilled workers (HY-TEN Ltd., 2013; Express Reinforcements Ltd, 2013). Alternatively, traditional rebar can be disposed of altogether in cases where fibre-reinforced concrete can meet functional requirements (Bjegovic et al., 2014).

4.3.1.2 Improvements in design practice

In additional to novel products, improvements in typical design practice could yield significant reductions in material use. For instance, Moynihan and Allwood (2014) assessed the scope for reduced rationalization in a study of 23 steel framed buildings produced by 3 leading UK engineering firms. When designs were assessed against Eurocode 3, it was found that the average utilization ratios (U/R) of beams and columns were 0.54 (by mass) and 0.49 respectively, suggesting that around half of the steel specified was excess to requirements. Moynihan argues that using stock member sizes it should be possible to consistently achieve a U/R around 0.9, potentially reducing the mass of steel used in beams by 36%. If applied across UK construction, this is a potentially dramatic saving; however there are some reasons to be sceptical of the magnitude of this claim. In addition to omitting vibration considerations, the study omitted 21% of all beams and columns present in the designs due to perceived overload or insufficient information. It would seem reasonable to speculate that beams that are corrected to non-failing sections through subsequent redesign may exhibit higher U/R than the project average. Furthermore, the two case study buildings exhibiting the lowest U/R were unusual ring constructions that do not account for a large share of UK steel-framed construction by mass. The remaining structures, whilst generally typical designs for their respective uses do not represent the distribution of steel structures produced in the UK. Nearly half the structures assessed were low rise schools, which do not represent even close to half of annual UK steel framed construction. As noted by the authors, the lowest U/R were frequently observed in the roofs and 'other' beams from small floors and miscellaneous areas. Analysis of the supporting information shows an average U/R across these 'other' beams of only 0.23, and across roofs of 0.35 (or 0.31 if outlier building 10 is excluded). The combined effect of these elements is to reduce the building average U/R. However, whilst these concerns may suggest it is unrealistic to extrapolate a 36% potential saving across UK steel construction as a whole, they do not undermine the central point that significant steel savings can be made through reduced rationalization. The authors argue that "*rationalization can be reduced by at least two methods: by increasing the time engineers have to design buildings, or by greater use of existing steelwork design and optimization software. Both strategies involve extra cost but reductions in steel mass may offset these, particularly as weight savings compound*". To motivate this they recommend that "*environmentally minded clients, or those who simply do not like waste, could reduce excess material in the buildings they commission by specifying a minimum average U/R*". This could easily be included alongside the material efficiency targets recommended in BS 8895.

4.3.1.3 Modern methods of construction

The full benefits of Modern Methods of Construction (MMC) and Off-site Manufacturing (OSM) have yet to be realised despite more than a decade of sustained guidance and advocacy (WRAP, 2007). Studies have repeatedly demonstrated that adoption of at least partial off-site fabrication can reduce material use and embodied carbon compared with traditional methods (Krug & Miles, 2013). For instance Monahan and Powell (2011) found that when compared with traditional methods of construction an affordable 3-bed MMC house resulted in a 34% reduction in embodied carbon. Though there has been some increase in the use of off-site methods on large commercial projects, the house-building industry has remained remarkably reticent to the adoption of MMC (Pan et al., 2007). The 2013

Offsite Housing Review argued that the benefits of faster build times, better quality of build and improved sustainability do not yield any commercial advantage for housebuilders in the current market (Construction Industry Council, 2013). Without substantial intervention, such as increasing the requirements of the Building Regulations in relation to operational energy or development of new models for housing delivery, offsite construction is likely to remain a Cinderella system.

4.3.2 Designing for longevity

As Grinnell et al. (2011) point out "*buildings which are rendered obsolete significantly before their intended design life cannot be considered sustainable*". The unfortunate reality is that the majority of structures are demolished before the end of their design life for reasons that are unrelated to structural performance (Love & Bullen, 2011). Typical reasons for demolition include: declining operational and commercial performance, changing market demands, inability to attract tenants, high maintenance and repair costs, poor marketability, broader area redevelopment, or a simple impression of the building as old or inefficient (Bullen & Love, 2010). The aesthetic conventions and economic factors that influence land use and buildings over long periods of time cannot be predicted by designers; however, buildings can be designed with the intention of adaptation (Guy, 2002). Thus, in many cases, the decision to demolish a structure reflects the poor adaptability rather than insufficient durability of a design (Kestner & Webster, 2010).

4.3.2.1 Adaptable design in new buildings

Two decades of research within the field of adaptable building design, has resulted in a range of approaches, set out by Grinnell et al. (2011) and summarised in Table 8. Largely these consist of design principles for new buildings that facilitate reconfiguration, easy access for maintenance and upgrade of services, and replacement of shorter life span components. This usually involves a design focus upon repetition, transparency or layering and creation of an easily comprehensible structural system. The provision of a certain amount of redundancy in the form of additional load bearing capacity is also common when future changes of use are considered. The use of modular construction and long spans to facilitate alternative internal arrangements are also common features. In addition to literature that focusses on adaptable design in new buildings, there is a burgeoning field dealing with adaptive reuse of existing structures.

4.3.2.2 Adaptive reuse of existing structures

Extending the lives of existing structures through effective redevelopment could significantly reduce the demand for core structural materials. This requires effective adaptation of old structures to meet new client needs and modern performance standards. This poses a significant challenge to designers but not an insurmountable one. This practice is increasingly common and banks of successful case studies are steadily becoming available (e.g. AdaptiveReuse.info, 2013). Love and Bullen (2011) provide a comprehensive overview of the associated barriers and drivers for adaptive reuse (albeit within the Australian market). Given the age and condition of the UK building stock, there is significant scope for reducing demand for additional structures and materials through increased adaptation and refurbishment of existing structures. However, the balance between demolition and refurbishment remains a subject of debate (Power, 2010). A better understanding of the financial, temporal and design barriers that lead to demolition being preferred to refurbishment within the UK could lead to savings in total life cycle emissions. There are a wealth of additional social and economic benefits to refurbishment as compared to demolition, and a great opportunity to preserve the historic, cultural and community value of the existing building stock (The Empty Home Agency, 2008; Power, 2008).

Table 8: Approaches to adaptable design (adapted from Grinnell et al., 2011)

Approach	Examples	Characteristics
Layering / Separation	Open building (Kendall, 1999)	Building viewed as a series of systems, subject to change at different rates
	Adaptable futures design structure matrix (Schmidt et al., 2009)	Justification of a strategy for identifying layers proposed
	Brand (1997)	Interactions between layers to be minimised/ controlled so as to allow flexibility
Uncertainty	Redundancy and loose-fit (Gorgolewski, 2005)	Acknowledge inherent uncertainty of future
	Design for multi-functionality (for an example see p80, Kronenburg, 2007)	No attempt at prediction of change
		Allowances made for general, unspecified changes
Decomposition / Reversibility	Design for disassembly (CSA, 2007; Guy & Shell, 2003)	Elements removable without damage to themselves or surroundings, building decomposable into constituent parts
	Diversified lifetimes (Fernandez, 2003)	Compatible with layering approaches, but often employed without reference to them
		Modularisation, standardisation, recycling
Technical Solutions	Standardisation / mass customisation (Davison et al., 2006)	Application of a 'solution' to the building problem, adaptability achieved through the use of technology
	Kit of parts (Schmidt et al., 2008)	Often synonymous with industrialisation of construction process
	Moveable components (for examples, see Schneider & Till, 2007)	Marketable products

4.3.2.3 Self-healing materials

A new raft of self-healing materials including metals, polymers, ceramics, coatings and concrete could also extend component and structure service lives (see Lark et al. (2011) for a wide ranging review). These materials respond and adapt to their environment and could potentially reduce maintenance costs and environmental impacts. Perhaps the most promising examples are concrete incorporating super-absorbent polymers or bacteria (Van Tittelboom et al., 2010). Though these materials are still the subject of extensive testing, the first complete building using 'self-healing bio-concrete' was completed in 2015 in the Netherlands. UK trials are also ongoing into a range of self-healing concretes through the M4L research programme. It will doubtless be some time before these technologies reach commercial production, and they are unlikely to significantly reduce carbon emissions in the period prior to 2050. However, they offer the opportunity to significantly extend structure service lives and reduce demand for replacement structures in the constrained carbon space beyond 2050.

Thus, it can be argued that the adoption of self-healing materials and adaptable design principles in new buildings, in combination with the adaptive reuse of existing buildings, could extend the service life of key carbon-intensive building elements such as structural frames and foundations, leading to reductions in required levels of new construction and virgin material production. However, to the author's knowledge, no studies have yet attempted to quantify the potential scale of this impact across the UK building stock.

4.3.3 Designing for deconstruction and material reuse

In the simplest sense, design for deconstruction (DfD) means considering end of use scenarios during initial building design (Institution of Structural Engineers' Sustainable Construction Panel, 2011a). Good design can ensure less damage to components and higher material recovery rates, thus maximising the volume and value of material that can be reused, ensuring high recycling rates of the remainder, and minimising waste to landfill. When considering embodied carbon, component reuse can displace the need for virgin material production. In this regard, deconstruction is preferable as it preserves the invested embodied carbon of materials, reducing the input of new energy in reprocessing or remanufacturing materials (Kibert, 2003).

The DfD concept emerged during the early 1990s (Kibert, 2003), and has been applied on a wide range of predominantly steel and wood-framed structures (see Densley Tingley (2012 pp. 14–18) for examples). Extensive guidance for designers has emerged, such as the checklists proposed by the Institution of Structural Engineers' Sustainable Construction Panel (2011) or the principles outlined by Kibert (2003). Davison & Densley Tingley (2011) identify 33 commonly cited design strategies for deconstruction, summarised in Table 9. DfD can be supported by a range of software tools outlined by Densley Tingley (2012 pp. 13–14), including Sakura – a whole life carbon appraisal tool that incorporates end of life options, intended for use at the conceptual or scheme design stage (Densley Tingley & Davison, 2012).

Despite the clear environmental benefits and associated credits within environmental assessment schemes (Davison & Densley Tingley, 2011), the application of DfD is subject to a number of constraints, outlined by Guy (2002). Chief amongst these is the "*difficulty in convincing clients to pay slightly extra for their project to be designed for deconstruction, when the benefit is not incurred until some point in the future when the project is deconstructed and then the value of the salvaged materials can be claimed*" (Densley Tingley & Davison, 2012). Without the common use of whole life costing and confidence in a future reuse market, it is difficult to make an economic case for DfD.

Over recent years, demolition has also become increasingly preferred to deconstruction due to time constraints, health and safety concerns and financial considerations. Although recycling of construction materials has increased during the last decade, reuse has declined substantially (Kay & Essex, 2009). For example, of the one million tonnes of steel arising from UK demolition in 2007, only 30,000 tonnes were reclaimed for reuse (3%). Meanwhile, only 1.5% of 2007 new build steel demand was met by reclaimed steel (Kay & Essex, 2009). By comparison, other estimates have suggested that across the EU between 10 and 37% of steel is reused, depending on section type (Addis, 2006). Cooper and Allwood (2012) have suggested that up to 50% of many common steel and aluminium construction products could be reused, though this is subject to a number of barriers (Densley Tingley & Allwood, 2014). There is clearly significant potential for greater reuse of high value and carbon-intensive metals within UK construction, with steel reuse the subject of two Innovate UK funded research projects at the time of writing (Gateway to Research, 2015). The potential also extends beyond steel, with an estimated 10 million tonnes of construction materials that could be reused each year (Kay & Essex, 2009 p. 6).

One means of exploiting this potential is encouraging greater use of novel ownership structures. For example, the leasing of major structural components such as roofs. In such a scheme, occupiers would lease out the roof for a long period corresponding to the anticipated structure life (such as 40 years) after which time the roof owners and installers would dismantle and reclaim the materials for reuse on a similar project. This approach has already been adopted by a small number of firms providing steel portal frames, temporary bridges and event staging. This model could potentially be applied to elements of many more structures with short anticipated lifespans and standardised designs. Component level precedents already exist in established take back schemes for plasterboard and PVC windows.

Table 9: Strategies for design for deconstruction (from Davison & Densley Tingley, 2011)

1	Ensure there is an integrated set of 'as built' drawings
2	Design building so elements are layered according to anticipated lifespan
3	Use connections that can be easily removed
4	Avoid use of adhesives, resins & coatings which compromise reuse potential
5	Develop a deconstruction plan during the design process
6	Design components and joints to be durable, so that they can be reused
7	Provide identification of component types
8	Use a standard structural grid
9	Design for maximum flexibility - to preserve the building as a whole
10	Whole design team, client & contractor need to be on board
11	Ensure structural systems can be easily deconstructed
12	Identify the design life of different elements
13	Provide access to all parts & connection points
14	Use the minimum number of connectors and limit the different types
15	Minimise the different number of materials used
16	Design the geometry to be simple
17	Allow extra time to ensure DfD is incorporated
18	Train contractors in DfD, where required
19	Establish targets for the percentage of the building that can be reused
20	Where possible design in passive measures instead of active service elements
21	Provide a full inventory of all materials and components used in the building
22	Size components to suit the means of handling
23	Use prefabrication and mass production where possible
24	Select easily separable materials, with good reuse potential
25	Avoid composite systems
26	Plan service routes so that they can be easily accessed and maintained
27	Designation of 'fixing free zones' to maximise lengths of material for reuse
28	Use modular design
29	Design for locally produced materials
30	Allow for safe deconstruction
31	Provide adequate tolerances for disassembly
32	Provide spare parts & storage for them
33	Avoid secondary finishes that cover connections

More projects could incorporate the reuse of existing foundations. Foundations are often responsible for the largest environmental impacts of a structure, requiring high volumes of concrete and steel. A wide range of reasons restrict their reuse in practice but many of these can be overcome (Addis, 2006 pp. 89–93). The last decade has seen the dissemination of extensive best practice guidance from CIRIA and the BRE (RuFUS, 2006; Chapman et al., 2007). This not only includes advice on reuse of existing foundations but steps to enable future reuse of new foundation designs. An estimated fifth of global steel production is used in foundation rebar (Moynihan & Allwood, 2012). Simply leaving this material in the ground at the end of a structure's life is a tremendous waste. The development of technologies that can enable more effective recovery of this steel, or more frequent reuse of foundations, could significantly reduce new material demand.

In the long run ongoing efforts to develop fully reusable structures for common project types represents the next milestone for DfD. For instance, the RE-Fab project intends to create a framework for the development of Flexible Life Buildings (ASBP, 2015). Following a successful feasibility study and development of common protocols, the intention of the RE-Fab project is to develop a fully adaptable and demountable house for repeated deconstruction and reuse. The increased use of BIM also offers opportunities to maximise the benefits of DfD through comparative assessment of deconstruction strategies (Akbarnezhad et al., 2014). In the meantime, as summarised by Kestner & Webster (2010): "*market forces are not sufficient*" and "*a combination of green building rating system incentives, price increases for new materials and possibly tax or regulatory incentives*" will be needed to drive demand for DfD. Rios et al. (2015) highlight a range of state policies implemented in the U.S. that could support DfD; however, it is unlikely that comparable policies would garner sufficient support in the UK parliament at present. In addition to regulatory drivers, increased testing and re-conditioning facilities will be needed to support greater reuse.

4.4 Alternative materials

The majority of structures in the UK are currently built using steel, concrete and masonry but similar structures can be produced using a variety of traditional and modern building materials with lower environmental impacts (Cabeza et al., 2013). The numerous options can be broadly grouped into materials derived from biotic substances and materials that incorporate wastes, recycled or reused content. These are considered in turn.

4.4.1 Biotic materials

A range of renewable materials derived from trees and crops have been used in construction for centuries. Many of these materials require less energy for production and processing than common non-renewable materials, such as steel and masonry, largely due to the avoidance of high temperature production processes. In addition to typically offering lower cradle-to-gate emissions, biotic materials sequester carbon through photosynthesis. Such sequestration is often considered as a carbon store when conducting LCA studies. The precise attribution of any benefits from carbon storage remains a source of much debate (e.g. Purnell, 2012; Sathre et al, 2012). Any LCA is arguably incomplete without considering the source and fate of the carbon stored in a biogenic product. Such carbon may be released to the atmosphere at the end of the product's service life depending upon the particular means of disposal. Thus assumptions made about end-of-life scenarios become a key part of the LCA. For example, after building deconstruction, postuse wood may be re-used, recycled into other products (such as chipboard), incinerated for energy recovery or taken to landfill. Each of these options will result in different emissions or retention of carbon. The matter is further complicated as, where incinerated for energy recovery, the waste wood may be used to displace fossil fuels.

Although this issue is complex and the debate continues within academia and industry, the common carbon footprinting standard, PAS 2050, was updated in 2011 to allow for the inclusion of biogenic carbon storage, and the approach has been standardised in EN 16449: Wood and wood-based products - calculation of sequestration of atmospheric carbon dioxide. UK wood products are now commonly reported with figures for a range of end-of-life scenarios (e.g. Wood for Good, 2014), allowing the practitioner to consider all potential outcomes. It is important to note that even when potential sequestration benefits are excluded, most comparative life cycle assessments of common structural materials still assign better results to wooden structures (Buyle et al., 2013). Similarly, comparative studies of straw bale (Sodagar et al, 2011) and hemp-lime (Ip and Miller, 2012) excluding sequestration have also demonstrated lower embodied carbon than common walling materials. Thus, although the magnitude of the calculated carbon savings may vary, in the majority of cases, the inclusion or exclusion of sequestration should not determine the final choice of materials where the lowest carbon solution is sought.

An analysis of recently published EPDs by Hill and Dibdiakova (2016), showed that when sequestration is considered *"irrespective of the timber product used and its associated embodied GWP emissions, the use of timber in construction always acts as a net carbon store."* At an aggregate level, a study commissioned by the ASBP suggested that annual carbon sequestration across UK construction is currently of the order of 6-10 $MtCO_2e$ (Sadler & Robson, 2013). By adopting policies that encourage the use of bio-renewable building materials, the authors estimated that up to 22 $MtCO_2e$ could be sequestered per annum by 2050. However, this would require an estimated threefold increase in the intensity of use of bio-renewable building materials. There is doubtless some benefit even to the temporary storage of carbon given the temporal significance of greenhouse gas emissions, as discussed in Section 2.5.4.

The most prominent biotic material is undoubtedly timber; however, there are many examples in the commercial and housing sectors of structures produced using other natural materials such as straw, hemp and earth (MacDougall, 2008). Indeed, the UK sports numerous examples of buildings dating back to the 19th century made from these traditional materials (Walker 2007). There has been a small scale renaissance in these longstanding techniques, with hundreds of projects completed in the last decade (De Wilde et al., 2010). Whilst there is limited scope for revival of traditional approaches at scale, the opportunity to greatly expand the use of biotic materials through novel applications is substantial. Recent research, innovative architecture and product development has sought to combine traditional materials with modern methods of construction. This has resulted in a variety of low carbon building frames and envelopes. The following sections review a number of prominent examples.

4.4.1.1 Prefabricated panellised straw and hemp-lime structures

The use of panellised prefabricated timber and straw bale systems such as ModCell® (ModCell, 2012) and ecofab (ecofab, 2013) has been largely responsible for a revival of interest in straw bale construction. ModCell® panels use Cross Laminated Timber (CLT) frames filled with wheat straw stacked on timber dowels and braced with steel reinforcing bars (see Figure 12). The panels are fixed together using long screw connections and coated with a vapour permeable plaster (6:1:1 lime to cement to sand). The panels are constructed off-site in flying factories, reducing material use and risks of fire or moisture ingress. The panels were first used at the University of the West of England's School of Architecture in 2002 (Wall et al., 2012). There are now several hundred recently completed straw bale structures in the UK including offices, educational buildings, retail premises and three-storey

Figure 12: Typical two bale Modcell panel (Maskell et al., 2015)

load bearing homes (Chatterton, 2013). The development of these novel products has resulted in a transition from these materials being seen as suitable for the home build project of an "*eccentric individual*" (De Wilde et al., 2010) to being used on speculative commercial developments for the open market (BBC News, 2015). In spite of this, many long-standing concerns persist in the minds of clients and construction professionals. For instance, Hamilton-MacLaren et al. (2013) found straw bale to be the least acceptable form of wall construction in a survey of 572 potential UK home purchasers. 39% of respondents to the survey said they would not purchase a house built with straw bale because of perceived concerns with fire performance, durability and high maintenance requirements. This is in spite of tests showing straw panels can be exposed to fire for more than four times the regulated period without experiencing failure (Wall et al., 2012); and maintenance requirements being no greater than typical alternatives. If such negative perceptions can be overcome, there is great potential for the expansion of panellised straw bale construction. A study by Watson et al. (2012) demonstrated there is more than sufficient straw supply to meet annual construction of all commercial and residential buildings in the UK. The low cost-sensitivity of the materials, short construction times, and exceptional thermal performance in use (typical bales achieve a thermal conductivity of 0.055–0.065 W/mK (Sutton, Black & Walker 2011)) could pose an attractive package to developers in future. The primary deterrent for mass housebuilders is the wall thickness of 450-500 mm. However, as indicated by Smyth et al. (2008), ultra-low U-value walls are typically much thicker than standard wall constructions irrespective of the technology used. As building regulations are tightened to require higher thermal performance, thicker options such as straw bale will become more attractive.

Hemp has undergone a similar resurgence with several hundred monolithic hemp-lime buildings constructed in the past decade (Pritchett & Burbidge, 2014). Efforts are also underway to develop a commercially competitive, pre-fabricated, pre-dried, panelised system of hemp-lime construction through the HEMPSEC project (University of Bath, 2016). Pre-fabricated hemp-lime panels have already demonstrated exceptional hygrothermal performance (Shea et al., 2012), excellent moisture buffering (Latif et al., 2015), exceptional air tightness (Daly et al., 2012), a negative carbon footprint when sequestration is considered (Ip & Miller, 2012) and delivered significantly lower than predicted energy bills on exemplar commercial projects such as M&S' Cheshire Oaks store (Faithful+Gould, 2013). The historic challenges preventing best performance in hemp construction mainly stem from undertaking the wet casting process on site. The use of panels that have been pre-dried offers better quality control, shorter construction times, and an extension of the suitable construction period into colder months. Further detail on advances in straw bale and hemp-lime construction can be found in overviews by Sutton et al. (2011a and 2011b).

A similar prefabricated approach was adopted in preparing the novel thatch cassette cladding used on the University of East Anglia Enterprise Centre (Pearson, 2015). The panels were prepared in barns over the winter period by local thatchers then installed in a similar manner to conventional cladding. This provided a source of local employment during the winter downturn as well as a façade with exceptionally low embodied carbon that met Passivhaus performance standards.

4.4.1.2 Biocomposites

Novel biotic materials are also under development, including a range of biocomposites that are typically comprised of natural fibres, such as flax, jute or hemp, in a polymer matrix derived from agricultural wastes, vegetable oils or corn starches. These have been incorporated into construction products through collaborations such as the BioBuild Project (NetComposites Ltd, 2014). One particularly promising example is the development of bio-based façade panels (see Figure 13). These pre-fabricated external wall panels incorporate a window and can be specified as a wall element with no internal finish and an external architectural finish. The core structure is formed from a computationally optimised biocomposite with an outer skin of biopolyester resin reinforced with flax fabric overlaying a layer of cellulose insulation. The product retains tremendous architectural flexibility and has been demonstrated to perform well across a range of standard performance tests. The materials forming the panel cost only a few euros per kilo; however, the current labour intensive manufacturing process results in costs 20% greater

Figure 13: 'Bio Build Facade System in Biocomposites' exhibited at Ecobuild by 3xn

than benchmark products. Industrialisation, automation and mass manufacture of the panels could significantly reduce the inhibitive labour costs and result in a cost competitive product with significantly lower carbon footprint than current cladding options. Facades typically represent 15-20% of total embodied carbon and construction costs on commercial projects (Cheung & Farnetani, 2015); thus any cost competitive solution offers the opportunity to displace a sizeable volume of carbon-intensive metal production. Other applications of non-structural biocomposites, such as internal partitions and suspended ceilings, are also under development.

4.4.1.3 Novel applications of timber

Driven by expanded advocacy groups and novel technologies, timber has seen a minor resurgence in recent years and there is scope for increased use across a range of market segments. The following paragraphs consider some of the technologies driving these changes across domestic, retail and commercial structures.

Despite well documented sustainability credentials, timber frame only accounted for 7% of housing completions in England between 1990 and 2009 (DCLG, 2010). This share has risen slightly in the last few years and is higher in certain parts of the UK, such as Scotland (where it accounts for 29% of the market). In the years up to and following the recession, timber also began to take a non-negligible share of the market for low rise flats (1-3 storeys). These market shares remain well below many other developed countries, such as Sweden, USA and Australia, where up to 70% of the housing stock is timber frame (Harris & Borer, 1998 p. 109). There is scope to increase timber use in housing, particularly through the use of MMC such as Structural Insulated Panels (SIPs). SIPs were first introduced in the USA in the 1930s, and came to the UK in the 1970s. However, for a long period the technology received minimal development, with the majority of products being two sheets of orientated strand board glued around a polystyrene or polyurethane insulation layer. Recently, a range of high performing SIPs incorporating phase change materials (Medina et al., 2008); waste products; and natural insulation such as sheep's wool (Corscadden et al., 2014) have entered the marketplace. These options offer improved in use performance and reduced embodied carbon. As Part L requirements tighten, these options will become increasingly attractive to developers. The trend towards building taller residential structures could also be met through the use of novel engineered timber products. For instance, the 9-storey Murray Grove Tower in London, took advantage of Cross-Laminated Timber (CLT) construction. Like glulam, CLT is constructed from lamellas of timber bonded together with permanent adhesives (see Sutton et al. (2011a) for an overview). Advocates envisage that the increased use of CLT and glulam should open up opportunities for timber use to become commonplace in domestic and commercial structures of 6-10 storeys (Lawrence, 2014). TRADA has even published scheme designs for 12-storey structures.

A number of high profile glulam and timber-steel hybrid structures have also been completed in recent years, particularly long span retail structures for clients such as Tesco and Sainsbury's (Hopkinson, 2011). These have demonstrated comparable build times to steel framed structures with significantly reduced embodied carbon. Timber-steel hybrid flooring for multi-storey construction offers the opportunity to further reduce embodied carbon by displacing concrete floor slabs, reducing structure weight and corresponding frame and foundation sizes, whilst allowing for easier reuse of steel components compared with standard composite construction (Okutu et al., 2014). As practitioners become more experienced with engineered timber and connection design for hybrid structures, this type of construction could become commonplace.

The coming decades also offer substantial opportunities to increase the use of British grown timber (Smith, 2015). Over the next 50-year period the UK will have a several fold increase in hardwood availability and 29% more home-grown softwood available for use (Forestry Commission, 2014). Currently, of the 5 million m^3 of sawn wood used in construction, only 20% comes from UK-grown stock, and nearly all engineered timber is imported (Smith, 2015). Small-scale development of novel processes for utilising species such as Douglas fir, Sitka spruce and larch in engineered timber products (e.g. Brettstapel, CLT and glulam) show great potential for expansion. For instance, research has shown that the use of home-grown Sitka spruce for CLT production is feasible, though this has yet to be demonstrated at commercial scale (Crowford et al., 2015). With CLT consumption set to expand significantly, there is an opportunity to halve the transport distance and create security of supply through establishing UK production facilities. Options such as this and the development of Welsh Brettstapel production could support local employment in manufacturing and contribute towards the Construction 2025 goal of leading the world in low carbon and green construction exports.

4.4.2 Materials incorporating wastes, recycled or reused content

The specification of recycled content targets is now commonplace on UK construction projects. Prior to recent funding cuts, WRAP completed an extensive body of work supporting the delivery of higher recycled content and material reuse. This included guidance for practitioners on measurement of recycled content, specification of products, example contract wordings and case studies (WRAP, 2009a). This general guidance was supported by a detailed guide to the recycled content of mainstream construction products (WRAP, 2008a) and a reclaimed building products guide (WRAP, 2008b). Both these documents included extensive supplier directories. In spite of these efforts the current reclaimed structural components market is commonly depicted as "*small and poorly integrated into supplier networks*" (Institution of Structural Engineers' Sustainable Construction Panel, 2011b). Meanwhile, the majority of building products contain low levels of recycled content. However, a range of novel masonry units, concretes and polymer products manufactured using consumer, agricultural and industrial wastes are slowly emerging from research into commercial production. The following sections provide a brief overview of some promising developments.

4.4.2.1 Fibre reinforced polymers

Fibre reinforced polymers (FRP) are a group of lightweight corrosion-resistant materials with flexible choices in shape and appearance, often containing high recycled content (which is strongly supported by building codes). FRP materials normally consist of fibres that are glass, carbon or plant based, mixed with a binder resin and a series of additives (to alter appearance and performance). Over the past few decades FRP composites have been increasingly utilised in the construction of bridge decks and modular structures. Other common applications are as formwork, railway sleepers, and external reinforcement for strengthening existing structures. See Hollaway (2010) and Stewart (2011) for comprehensive overviews. A new generation of all-composite structural units and novel hybrid structures may significantly expand FRP use in buildings. For example, polymer matrix SIPS, comprised of composite sheets sandwiching an insulating layer, are now readily available. A variety of SIPS incorporate insulating layers made from recycled materials such as glass (Ambiente, 2012) and packaging (Deutsche Composite GmbH, 2012). FRP rebar has been used in the US since the 1980s and is now becoming cost competitive with steel rebar for some applications. The extended service lifetimes, reduced weight, reduced maintenance requirements and the potential for incorporating recycled content can lead to reduced carbon emissions using FRP materials (Halliwell, 2010). However, the magnitude of the embodied impacts has been shown to vary widely depending on the component materials, manufacturing processes, and assumptions made about end of life disposal (Zhang, 2015; Halliwell, 2010). A range of novel bioresins with very low life cycle impacts are entering FRP production within other industries such as automotive manufacture (Halliwell, 2010). The widespread application of these new materials in construction products offers sizeable carbon reduction opportunities.

4.4.2.2 Low carbon concretes

As discussed in Section 3.5.2, the carbon emissions associated with concrete production are substantial and can be reduced through improvements in cement production efficiency, replacement of clinker by supplementary cementitious materials (SCM), or replacement of cement with other binders, such as sulfoaluminate clinker, geopolymers, and MgO cements (see Habert (2014) for a comprehensive overview of options). As set out in the recent UK cement industry roadmap, improvements in production facilities, increased use of conventional SCMs (such as GGBS and fly ash) and alternative fuels are unlikely to yield emission reductions of more than 10-20% by 2050 against current levels (WSP et al., 2015c). However, there are a range of emerging technologies that could yield additional reductions (see Hasanbeigi et al. (2012) for a review of 18 prominent examples).

A number of recent advances in SCM research, reviewed by Juenger & Siddique (2015), are being used to demonstrate the viability of novel waste streams including polymeric wastes such as tyre rubber (Pacheco-Torgal et al., 2012); several agricultural wastes (Shafigh et al., 2014); incinerated sewage sludge ash (Donatello & Cheeseman, 2013); plastics (Siddique et al., 2008); glass (Tan & Du, 2013); textile fibres (Wang et al., 2000); coal combustion by-products (Siddique, 2010); steel slags (Bian, 2011) and wood ash (Siddique, 2012). Though it is unlikely that any of these options will be produced on the same scale as conventional concretes in the period up to 2050, each may make a small contribution.

Similarly a number of geopolymeric cements (such as E-Crete, Geo-Blue Crete, and banahCEM) have entered the market in the past decade and offer a very low carbon alternative to OPC (McLellan et al., 2011). However, despite decades of research, a lack of national standards, long-term performance data and practitioner knowledge still restrict their use to certain niche applications (Van Deventer et al., 2012; Heath et al., 2013). Though a study of commercialisation in Australia identified some difficulties in establishing material supply chains, the core challenge was perceived to be the "*scale-up of industry participation and acceptance of geopolymer cement*" (Van Deventer et al., 2012). A scoping study for the UK expressed similar concerns regarding the "*notoriously conservative*" nature of the UK industry (Heath et al., 2013). The UK study did identify significant material resources that could support early production, including large stockpiles of PFA, though also expressed concerns that supplies of common precursors may be exhausted swiftly if there was a rapid expansion in production alongside the closure of coal fired power stations. Precast elements (including blocks) were identified as the best initial route to market for manufacturers, potentially avoiding issues of acceptance from construction workers (as they may not realise the difference). A related rapidly expanding field of research considers geopolymer composites (such as fabric-reinforced geopolymers) that could combine reduced carbon emissions with improved ductility and durability (Sakulich, 2011). However, irrespective of recent advances in this research it will likely be decades before production reaches a substantial scale.

4.4.2.3 Completely recyclable concrete

Around half of all construction and demolition waste is concrete rubble. Downcycling of this material is commonplace in road construction and a range of geotechnical applications (Cardoso et al., 2015). Indeed, in 2015, recycled and secondary aggregates accounted for 29% of the GB aggregates market, nearly three times higher than the average market share in Europe (MPA, 2015). Despite this there remain few commercial suppliers, arguably restricting greater uptake

(Institution of Structural Engineers' Sustainable Construction Panel, 2010). Although current uses are preferable to disposal, the greatest potential carbon savings can be made by encouraging a shift from low-grade to higher-grade applications. Some construction and demolition waste is currently recycled as aggregate in new concrete production, subject to the limits of BS 8500-2. Typically, replacement of 20%–30% of natural aggregates by recycled concrete aggregates will have no significant impact on the durability of concrete, but can reduce the compressive strength and affect workability. This is principally because the mortar and cement paste attached to the old stone particles increases water absorption.

Recent research has sought to develop Completely Recyclable Concrete (CRC) with a chemical composition similar to that of raw cement materials (De Schepper et al., 2013). The intention is that the concrete rubble from a demolished CRC structure can then be used in the production of new cement without any modification. LCA has demonstrated that this can achieve significant reductions in global warming potential, particularly for low clinker content mixes (De Schepper et al., 2014).

Recent research has sought to develop Completely Recyclable Concrete (CRC) with a chemical composition similar to that of raw cement materials (De Schepper et al., 2013). The intention is that the concrete rubble from a demolished CRC structure can then be used in the production of new cement without any modification. De Schepper et al. (2014) demonstrated with an LCA that "CRC could significantly reduce the global warming potential of concrete". However, it should be noted that this study only estimated a small reduction in global warming potential attributable to the end of life recycling. Indeed the CRC1 sample discussed in the paper, which included some copper slag and fly ash but used CEM I cement, yielded only marginal improvements in global warming potential compared to a reference OPC mix. For the best case mix, CRC2, the bulk of the observed reduction in global warming potential was attributable to the use of blast furnace slag cement. This suggests that the first priority for emissions reduction in concrete manufacture should continue to be the increased application of SCMs, but that additional end of life solutions may make a modest contribution to achieving more stringent carbon reduction targets in the long term. The research team behind CRC are currently investigating a range of alternate mix designs with further reduced carbon emissions, including the extensive use of copper slag (De Schepper et al., 2015).

4.4.2.4 Low carbon masonry units

Conventional brick production is an energy intensive process responsible for a high volume of carbon emissions. These predominantly stem from the drying and firing processes which employ very high temperature, typically gas-fired, kilns. Around 66% of the UK brick industry's carbon footprint stems from combustion of natural gas and other fuels, with a further 14% from electricity usage and 20%

attributable to process emissions (WSP et al., 2015c).

Whilst some alternatives, such as unfired bricks, can prove suitable for non-load-bearing applications, their commercial production is typically in small quantities (Heath et al., 2009). Research is ongoing into the use of load-bearing unfired clay bricks that have been stabilised with a range of binders (Oti et al., 2008). Early tests on unfired clay bricks produced with commercial production technologies and stabilised with GGBS, suggest they should be suitable for low-rise load-bearing applications (Oti & Kinuthia, 2012). However, if such bricks were to enter into high volume production, they would be forced to compete for GGBS supplies with the concrete industry. At times of high demand, UK supplies of GGBS have already been exceeded and demand has depended upon German imports (Competition Commission, 2012). So there is likely a limit to the potential volume of production that GGBS stabilised unfired bricks could feasibly replace.

Researchers have also produced fired masonry units that incorporate a plethora of wastes. These include at least 43 different additives, see Muñoz Velasco et al. (2014) for a review. These waste create bricks (WCB) exhibit a variety of properties that may be beneficial for different applications (Raut et al., 2011). However, as noted in another comprehensive review by Zhang (2013): "*although many of the studied bricks made from waste materials meet the various standard requirements and a number of patents have been approved, so far commercial production and application of bricks from waste materials is still very limited*". Zhang suggests that this is related to the absence of relevant standards and the slow acceptance by industry and the public. In addition to overcoming negative public perceptions of waste and recycled materials (Oyedele et al., 2014), it is important to understand the reasons behind "*tepid*" interest from brick manufacturers (Zhang, 2013).

The UK industry produced around 1.95 billion bricks in 2015 across 60 brickworks (ONS, 2016). Similar to the steel and cement industries, the brick industry is dominated by four international manufacturers (Forterra, Ibstock Brick Ltd, Michelmersh Group and Wienerberger Ltd). The industry has been reporting against a set of sustainability KPIs since 2001 and is currently targeting a 5% reduction in CO_2 emissions generated per tonne of bricks manufactured by the end of 2020, against a 2011 baseline (Brick Development Association, 2013). The industry also developed a Resource Efficiency Action Plan in 2013, which included actions such as "*promotion of the benefits of recycled and alternative raw material usage in the overall production process by case studies*" (WRAP & Brick Development Association, 2013). Thus there is some evidence of ambition within the industry to adopt low carbon alternatives including waste materials. However, much like the heavily consolidated steel and cement industries, changes in production are restricted by long investment cycles, high capital costs and desire for short payback periods (2-3 years) motivated by competition for capital within international groups.

Principal strategies for carbon reduction in the industry focus on the adoption of best available production technologies and reductions in product weight, which a recent industrial roadmap estimated could yield combined sector carbon reductions of up to 27% by 2050 (WSP et al., 2015c). It should be noted that this falls far short of the 61% improvement required by the GCB Routemap 80% reduction scenario (previously discussed in Section 1.4.4). Reductions of such magnitude for conventional production would require installation of carbon capture technology which is unlikely to ever prove economic for individual production plants of this size. Thus, it could be argued that although the commercial manufacture of WCB currently appears financially unattractive to producers, in future it may be essential in achieving sector carbon reductions targets.

The scale of potential carbon savings from greater use of WCB is difficult to estimate. The EPD for generic UK brick production claims a global warming potential of 158 $kgCO_2e/t$ of bricks (BRE & Brick Development Association, 2013). It should be remembered that this figure represents only brick manufacture and excludes transport to site, mortar use and so on. The figures presented in commonly used databases are also typically higher (e.g. 240 $kgCO_2e/t$ of bricks in ICE v2.0). However, despite extensive studies on the mechanical and thermal properties of WCB, to date, there are few detailed life cycle assessments quantifying the potential carbon savings.

It is clear that although researchers have explored many potential alternatives to conventional clay fired brick production, without greater support for commercialisation these are unlikely to achieve widespread use. In the meantime the dominant manufacturers will continue to market 'green' products, such as the Forterra ecostock® range, which simply represent the use of best practice conventional production facilities.

4.5 Alternative business models

Innovation theorists argue that adoption of radical innovations, such as novel materials, requires the reconfiguration of existing socio-technical regimes and business models (Geels, 2004; Zhao et al. 2016). Much recent research on topics such as eco-innovation, resource efficiency and the circular economy has sought to understand how businesses embed sustainability into their purpose and processes. Bocken et al (2014) summarise the multitude of alternative approaches into a set of 8 sustainable business model archetypes. These include technological options to 'maximise material and energy efficiency', 'create value from waste', and 'substitute with renewable and natural processes'; social options to 'deliver functionality rather than ownership', 'adopt a stewardship role', or 'encourage sufficiency'; and organisational changes to 'repurpose for society/environment' or to 'develop scale up solutions'. Though much of the research in this field has focussed upon consumer products, the application of such options to firms operating in the built environment is a growing topic of interest (Cheshire 2016; Zhao et al. 2016). Although there are limited examples of construction firms fundamentally repurposing their business or undergoing substantial organisational changes, there are many widely cited examples of building product manufacturers offering new product service systems (Tukker, 2015). The most commonly highlighted examples are the Philips 'Pay per Lux' solution and Interface FLOR flooring services.

Under the 'Pay per Lux' model Philips maintain ownership of the lighting products whilst providing clients with the service of lighting for the duration of a fixed price contract. This incentivises the producer to improve the operating efficiency and facilitates recovery of all lighting products at the end of the building service life. Similarly, the Interface option provides modular floor coverings that are recovered at the end of the contract for reuse or recycling. Whilst these examples have received extensive press coverage and promotion from groups such as WRAP, there is minimal evidence to suggest that they present an attractive and profitable proposition for construction product manufacturers. Few comparable offers have arisen amongst competitors and similar business models have yet to be widely applied to other construction products. Though it is essential to achieving the environmental and financial benefits of such a business model, the successful recovery of products under these contracts has also yet to be demonstrated in practice.

There are considerable uncertainties associated with business models that are dependent upon projected value retention over a prolonged period. Such a model depends upon a presumed future market for the product and the assumption that it will not be superseded by alternative approaches or products during the service periods. In the case of construction products, the service period can be many decades. After which it is assumed that the product can be recovered cost effectively and in suitable condition for further use. These uncertainties are not trivial, and consequently, it is unlikely that established market producers will seek to switch from their existing business models. New producers may need to enter the market, however, the construction sector has long suffered from notoriously high rates of small business failure. Achievement of the mooted environmental benefits of product service systems ultimately depends upon the survival of the company over multiple lifetimes of the product.

The barriers to greater adoption of product leasing were explored by the author in collaboration with the UK INDEMAND Centre during a series of three practitioner workshops at the 2015 Resource circular economy conference. The third workshop gathered input from 30 participants across the value chain on potential applications in the construction sector. A limited range of opportunities were collected as practitioners generally expressed concerns around liability and the relatively long construction product life times in comparison to consumer products. Participants suggested that some applications may be possible where reduced capital costs proved attractive to the client, but these may need to be supported by specialist finance vehicles given the timescales involved. A paper further detailing the results of these workshops was under preparation at the time of writing.

Beyond construction products, there are also few examples of novel models being adopted at a building scale (Cheshire, 2016). The most widely publicised example is the recent redevelopment of Brummen Town hall, where ownership of key building components including timber, mechanical and electrical installations, lighting, tiles and flooring was retained by the manufacturer. This, combined with the use of material passports that detail material composition and plans for extraction, ensured almost all material inputs should be reusable. A small number of companies also regularly lease temporary steel structures. For instance, the structural envelopes were leased for both the water polo and shooting arenas at the 2012 London Olympics. The steel trusses, supporting structure and PVC envelope were erected and deconstructed by ES Global, as described by Densley Tingley & Allwood (2015). Information about the truss use was recorded, then the steel was shot blasted, tested and certified before reuse on another building. Though these examples show promise, there are a limited range of clients for whom such an approach would be suitable.

Undoubtedly there are opportunities for the construction industry to learn from alternative business models that successfully support product longevity in other sectors; however, there are a number of key differences that restrict direct transfer. Principal among these are the extended time spans involved, the lack of component standardisation and the desired uniqueness of each construction project. Some of these barriers are explored further in Chapter 5.

4.6 Discussion

The previous sections introduced a range of alternative materials, design strategies and business models listed in Table 10 overleaf. The list includes some options that were not previously detailed due to the limited potential scale of their application in the UK. This includes niche construction methods using alternative materials such as earth (Pacheco-Torgal & Jalali, 2012); tyres (Peacock et al., 2010) and bamboo (van der Lugt et al., 2006). Each option is presented alongside a summary of suitable applications and a qualitative assessment of the immediacy and magnitude of associated carbon savings. Any carbon savings achieved from implementation of these options depends upon the particular material and project parameters, assumptions about the benefits of carbon sequestration and so forth. Thus the table should be viewed as a rough guide only.

Table 10: Summary of options for reducing the use of carbon-intensive materials in the UK construction sector

	Potential applications								Carbon savings	
	Residential	Retail	Offices	Education	Infrastructure	Other	Substructure	Superstructure	Immediacy	Magnitude
Alternative biotic materials										
Timber (traditional forms, SIPs, Brettstapel, CLT, glulam, timber-steel hybrid construction)										
Straw-bale (infill, load-bearing or composite panels e.g. Modcell®)										
Biocomposites										
Earth (rammed earth, unfired brick, cob, wattle and daub, adobe)										
Hemp (hempcrete and hemp-lime blocks and panels)										
Limecrete										
Bamboo (laminated or unprocessed)										
Cardboard (tubing or panels)										
Other alternative materials										
Geopolymer cements										
Geopolymer composites										
Completely recyclable concrete										
Self-healing materials										
Plastic (FRP, ETFE)										
Tyres										
Concrete and masonry units incorporating supplementary cementitious materials or aggregate substitutes such as:										
Industrial wastes (GGBS, fly ash, silica fume, pulp and paper mill residuals, coarse steel slag, copper slag, cotton waste, sewage sludge ash etc.)										
Consumer wastes (plastics, glass, ceramics, tyres, textiles)										
Agricultural wastes (rice husks, corn cobs, vegetable fibres, nut shells etc.)										
Construction and demolition waste										
Alternative business models										
Component leasing										
Other product service systems										

	Potential applications								Carbon savings	
	Residential	Retail	Offices	Education	Infrastructure	Other	Substructure	Superstructure	Immediacy	Magnitude
Design strategies										
Use of structurally optimised components (carpet/roll-out reinforcement; variable depth members etc.)										
Design for high utilisation ratios of standard components										
Design for longevity										
Design for deconstruction										
Adaptable design in new buildings										
Adaptive reuse of existing structures										

Key

Immediacy of carbon savings

Carbon savings incurred immediately
(e.g. through absolute reduction in material use or direct displacement of more carbon-intensive material)

Carbon savings incurred in long term
(e.g. over decades through reduced maintainence or reduced demand for new components or structures)

Magnitude of carbon savings

Substantial carbon savings
(e.g. provides zero or very low carbon alternative to conventional approach)

Minimal carbon savings
(e.g. provides <5% reduction compared with conventional approach)

The highlighted options in the review draw upon a diverse range of materials and approaches but share many common barriers to uptake. These barriers are explored in detail in the next chapter. The following discussion is structured around three key questions arising from the review. What are the critical research gaps? Over what timeframe can these options contribute significant carbon reduction? What combination of options may be required to meet sector and national carbon reduction targets?

4.6.1 What are the critical research gaps?

It is clear from the body of evidence reviewed that past research has suffered from a number of shortcomings. The academic research on low carbon materials focusses too much on developing new materials and not enough on ensuring current materials are used efficiently. This is reflected in the distribution of publications encountered in the literature review, far more of which focus on material innovation – particularly in concrete and masonry – and few of which focus upon the real material efficiency of current building designs. Similarly, though there is a wealth of detailed studies on the physical performance of materials, there is a corresponding lack of detail in determining their associated environmental impacts. Few studies provide detailed consideration of potential supply chains for low carbon materials and there appears to be an insufficient focus upon the realistic potential for commercialisation of novel materials. Similarly, there are few detailed studies addressing the barriers to greater adoption amongst construction practitioners, clients and building users. Future research should seek to address these shortcomings and strike a balance between developing innovative materials, exploring factors preventing best practice in industry, and preparation of more practical guidance documents.

4.6.2 Over what timeframe can these options contribute significant carbon reductions?

For many options it is difficult to determine a realistic timeframe for adoption and the potential scale of associated carbon reductions. However, some general points can be made.

Though authors have argued that DfD is "*the most important green design strategy for achieving material sustainability*" (Kestner & Webster, 2010), it is unlikely to yield sizeable carbon emission reductions in the timescale required to avert dangerous levels of climate change. The design life of buildings is typically greater than the 35 years or so in which significant reductions in carbon emissions must be achieved. The buildings reaching end of life in the intervening period will predominantly have been designed with little regard for deconstruction. This is not to suggest that innovations in material recovery and reuse cannot yield carbon reductions through displacement of virgin materials in the interim period. The assertion is simply that DfD is unlikely to make a major contribution towards fast approaching carbon reduction targets, though widespread adoption of DfD principles should yield substantial reductions in the longer term.

Similarly, a number of the material innovations, particularly alternative cements, self-healing and completely recyclable concretes, may take many years to achieve commercial production, let alone harvest the carbon benefits associated with increased durability. In the meantime more immediate responses, such as encouraging careful attention to concrete mix design, with adjustment to key parameters and the appropriate use of admixtures, could yield significant reductions in embodied emissions (Purnell & Black, 2012; Purnell, 2013; Minson & Berrie, 2013). Many of the more advanced materials mentioned in the review will play a key role in ensuring the viability of construction in the restricted carbon space beyond 2050. However, the majority of options that are already commercially available generally exhibit a smaller range of applications and potential carbon reductions.

4.6.3 What combination of options may be required to meet sector and national carbon reduction targets?

Allwood has contended that to achieve Construction 2025 targets the sector should seek to use "*half as much material for twice as long*" (Allwood, 2015). However, it is doubtful that either of these goals is imminently achievable. Whilst the demonstrated scope for material efficiency through design is significant, there is no evidence to suggest it amounts to halving material use. Even the best examples produced to date have only shown potential reductions of around a third of certain materials used for some elements of particular structure types. Meanwhile the prospect of doubling structure lifetimes poses a serious risk to investors and goes against the current trend of shorter lifetimes and faster turnover of stock. It is likely that achieving carbon reductions of the order required will necessitate a broader combination of the options described, including significantly increased use of alternative materials.

Critics of alternative, particularly biotic, materials frequently suggest that concerns surrounding durability should prevent specification. However, to this author's knowledge there is no published evidence suggesting that the real building service life achieved in practice, as opposed to the design life, is any longer for more durable materials such as steel. Research has repeatedly suggested that the common reasons for building demolition are almost entirely unrelated to material durability.

Given the uncertain scope for uptake of each of the described options, the most dangerous fallacy is that any individual option could prove sufficient in itself. As Paul Ekins is fond of saying with reference to the selection of energy technologies:

"*you can pick any option you like, so long as it is all of them*". A similar approach will likely be required in construction if carbon reduction targets are to be achieved.

4.7 Summary

The supply chain analysis in Chapter 3 clearly identified that in order to meet strategic carbon reduction targets the UK construction industry must reduce the aggregate use of materials with carbon-intensive supply chains. It is therefore imperative to identify viable alternatives, be they novel materials, design strategies or business models that support reduced material use.

This chapter compiled a list of such options, collating literature on material efficiency strategies, alternative materials, and novel business models for the first time. This is the most comprehensive review of available alternatives to date and the resulting review documents highlight a number of common features and challenges. The majority of options leverage novel manufacturing and design technologies; apply MMC to traditional materials; or promote increased use of reused and recycled materials and best design practice.

Though a wide variety of alternative materials are presented in the literature, in many instances researchers have yet to assess the potential supply chain impacts of greater deployment or address the factors preventing adoption by industry practitioners. For many novel construction products, long product development and commercialisation periods, combined with current market dynamics, could significantly restrict the speed and scope of application. Consequently, few of the identified options are likely to achieve significant deployment in the period covered by current carbon reduction targets. Those products that are market-ready have a limited range of applications and often appeal only to certain types of client. There are also few viable material options for certain project and structure types, particularly tall buildings.

Similarly, though the body of literature providing design guidance has grown extensively, there is limited research tracking adoption of this guidance in practice. For instance, despite over two decades of research developing extensive guidance on design for deconstruction, research demonstrating the adoption of these principals is limited to a small number of case studies with little quantitative evidence to suggest any substantive increase in adoption of these strategies across the industry. The same period has seen a decline in the recovery and specification of re-used materials. Novel design guidance, such as the ongoing BS 8895 series addressing material efficiency, must be better promoted if it is to achieve any substantial reductions in material use.

It is apparent from the review that a broad portfolio of options will be required and additional work must address their common barriers to uptake and combined scope of application. The shared barriers to adoption amongst industry professionals are the subject of the next chapter. Subsequently, chapters 6 and 7 will address the required levels of application and explore the policies and industry-led actions that could support greater adoption.

5. Barriers to greater use of low carbon materials in the construction industry

> *No other industry can be as emotive yet scientific, steeped in both cutting edge technology and traditional methods, and is as frustrating as it is inspiring*
>
> Anthony Heaton, Sustainability Advisor at BAM, 2014

5.1 Introduction

The appraisal of options, outlined in the previous chapter, revealed a wide variety of alternative materials are available in the UK marketplace. However, whilst there are many examples of their successful use, there remain a multitude of barriers to widespread adoption of alternative materials amongst practitioners involved in the design and construction process. Many of these barriers are not associated with technical performance but with perceptions or cultural norms within the industry. However, as highlighted by Watson. et al (2012), minimal qualitative work assessing these barriers has been completed. Understanding the barriers to adoption of alternative materials requires not only determining what must be done to demonstrate performance and gain acceptance but also an understanding of the root causes of the resisting behaviour and conservatism of industry practitioners (Jones et al., 2015). This chapter presents further insights from the literature review, alongside results from a practitioner survey and series of interviews exploring the barriers to adoption of low carbon materials in greater depth.

The chapter is arranged in the following structure. Section 5.2 reviews the barriers identified in the literature. Section 5.3 outlines the methdologies employed in the practitioner survey and interviews. Section 5.4 presents results of the survey and Section 5.5 discusses results from the interviews. Section 5.6 reflects upon the key issues that must be addressed and offers some potential solutions. Section 5.7 discusses the limitations of the research approach and recommendations for further studies. Section 5.8 concludes the chapter with a summary of the preceding sections.

5.2 Literature review

Numerous past studies have addressed barriers to particular forms of 'green', 'sustainable' or 'low carbon' building (Häkkinen & Belloni, 2011). Some of these studies take broad definitions of sustainability, incorporating economic and social factors (e.g. Williams & Dair, 2007), whilst others have focussed specifically on the environmental aspects of sustainability. However, these studies have tended to consider only operational carbon emissions (e.g. Kershaw & Simm, 2013), the adoption of energy-efficient technologies (e.g. Pinkse & Dommisse, 2009), or the achievement of regulatory targets that exclude embodied emissions, such as Zero Carbon Homes (e.g. Osmani & O'Reilly, 2009). Very few studies have focussed specifically upon the barriers to alternative material choice as a means of mitigating embodied carbon emissions. The following literature review is thus formed of two parts. The first considers the cultural and institutional barriers preventing sustainable innovation more generally within the construction industry. This draws upon literature addressing 'green' and 'sustainable' building, and more general application of innovation theories to construction. The subsequent section considers specific studies that address the adoption of particular alternative materials, and the limited qualitative studies addressing embodied carbon mitigation. The review concludes by summarising the barriers accumulated through the literature review described in the previous chapter.

5.2.1 Barriers to innovation in the construction industry

The general diffusion of innovations is well understood in theoretical terms (see Mahapatra & Gustavsson (2009 pp. 10–12) for an excellent summary). It depends upon a number of technological, institutional, economic and social factors, and is strongly influenced by the interaction of stakeholders. The institutional framework, established culture and historical events all affect the uptake of a new technology or practice. Old technologies are often 'locked-in' by market feedbacks, a focus on short-term advantages or sunk capital. Initially new technologies must exploit niche markets that afford opportunities to develop the technology through 'learning by doing, using and interacting', as well as time to establish supply chains and user-producer relationships. Growth beyond this phase typically necessitates institutional changes, entry of new firms and formation of advocacy groups. This requires the engagement of a variety of stakeholders whose beliefs, perceptions, knowledge and skills will ultimately influence uptake. Often these perceptions and attitudes may differ from the reality, but the perceptions and attitudes rather than reality determine behaviours (Hemström et al., 2011). Yet, whilst this general knowledge of diffusion paths is well established, its application to innovative material selection in the construction industry has been limited.

The construction industry is regularly characterised as a highly fragmented, risk-averse, supplier-driven industry (Sorrell, 2003; Jones, 2014). This conservatism is generally seen as a rational response to market conditions. Listed construction firms are typically concerned with minimising risk and increasing profits on their existing asset base by implementing incremental improvements in their practices. Motivated by the continuing prevalence of lowest cost tendering, the industry has become locked into a path-dependent improvement trajectory of cost and risk optimization, as described by Jones et al. (2015). This long-standing dependence upon lowest cost tendering has placed a strong downward pressure on income for contractors and resulted in the routine passing of risk along supply chains through extensive sub-contracting. This has led to an environment where "i*t is not in such companies' interests to instigate innovative solutions, whatever the notional imperative, as this would add to the risk, together with its concomitant up-front costs*" (Demaid & Quintas, 2006). New environmental challenges, such as the demand for greater resource efficiency and carbon reduction, are viewed by some as a threat to profit margins that depend upon the use of locked-in cost and risk efficient technologies.

This aversion to innovation is reinforced by "*clearly delineated relationships based on contractual obligations*" which "*constrain inter-firm relations and information sharing*", "*reinforce hierarchies and power asymmetries*" (Arora et al., 2014). The traditionally separated building process involving many parties often diminishes the ability of any individual to make holistic project decisions. Similarly, individual stakeholders often feel unable to enforce sustainable solutions 'down the line' (Williams & Dair, 2007); just ensuring minimum standards are met is difficult enough, let alone the adoption of best practice solutions. Innovation is reinterpreted as risk by additional stakeholders encountering a design as it progresses through the project stages. The need to overturn conventional partisan relationships and embrace a more systemic approach to construction has been repeatedly noted for decades (Egan, 1998; Sorrell, 2003; The Royal Academy of Engineering, 2010; The Edge, 2015). Despite this, contractual structures still regularly inhibit effective integration of design teams and the supply chain. Unfortunately, it is only through greater communication and early engagement of the full supply chain that the knowledge of all stakeholders can be fully leveraged. Without this early engagement project decisions are often made too late for cost effective or practical implementation (Kershaw & Simm, 2013).

A litigious industry environment consolidates this aversion to innovation and necessitates a high quantity of pre-implementation evidence for new construction products to establish legitimacy and achieve acceptance (Arora et al., 2014). Construction professionals typically rely on case studies to evaluate novel products, placing a heavy burden on 'others' to innovate first. Most construction firms employ small workforces and are limited in their R&D capabilities and absorptive capacity. Few firms have the capacity to comprehensively assess all aspects of a novel material and often the ability to exploit new technologies is dependent on specific human capital. The nature of the industry necessitates moving between temporary projects, often of a unique character with a changing roster of stakeholders. Consequently learning is done on a project to project basis with professionals developing perceptions and skills from their individual experiences. This unsystematic process of building up knowledge results in the sluggish diffusion of innovations (Roos et al., 2010; Pinkse & Dommisse, 2009). Knowledge development is further hampered by poor knowledge exchange from academia to industry (Moncaster et al., 2010). Where lacking knowledge of alternatives, practitioners substitute routines and rules of thumb, generally resulting in sub-optimal decisions (Sorrell, 2003).

Often this reluctance to innovate is compounded by outdated regulatory requirements, which lag behind the development of technologies and encourage firms to stick with conventional materials (Arora et al., 2014; Persson & Grönkvist, 2014). Indeed, construction firms often lack any substantive regulatory or client-led drivers to adopt innovations that enhance environmental sustainability (Demaid & Quintas, 2006). The combined effect of this prevailing industry environment and the lack of substantive drivers for innovation is a pervasive inertia. Glass et al. (2008) argue that this is the "*most significant challenge*" to any innovation in the UK construction industry as the "*normative position is overwhelmingly one of begrudging response*". They suggest that if the innovative materials, technologies, and skills required in delivering low carbon buildings are to be developed "*in the short term at least, change needs to be imposed top-down, and supported bottom-up with encouragement and reward.*" In the meantime a common view has developed that "*major changes in how building industry professionals are educated and trained, in government policy, in the relationships and roles of the various actors, and in the products, tools, and approaches used to create the built environment are simply not occurring at any substantial rate*" (Kibert, 2007).

5.2.2 Barriers to the adoption of alternative materials in the construction industry

In addition to general studies on sustainable innovation in the construction industry, numerous studies have addressed particular innovative materials, such as those presented in Chapter 4. Unfortunately much of this research has focussed on demonstrating the technical performance of alternative materials, with authors repeatedly noting a dearth of corresponding qualitative studies assessing the cultural, behavioural, or perceptual barriers to adoption within design teams (Watson et al., 2012; Wong et al., 2013). The bulk of qualitative research conducted to date has focussed either upon general approaches to material selection amongst design teams or barriers to the adoption of particular materials (e.g. timber) and narrow groups of materials that share a common characteristic (e.g. high recycled content). Little work has been done to synthesise the common barriers and address the underlying factors restricting uptake of alternative materials. The following section attempts to synthesise results from existing studies, before considering barriers to a more general group of low carbon materials.

The most comprehensive overview of factors preventing the selection of 'non-conventional' materials is provided by Zhang and Canning (2011). The authors assert that the principal barriers are the lack of associated short-medium term commercial benefits; effective marketing and dissemination of information on new materials to practising engineers; and supportive material performance data and full-scale demonstration projects. The authors argue that this can be combated through the addition of design guidance alongside effective marketing and stakeholder engagement. On the basis of this, the authors propose a model for introducing new materials. This model begins with identification of the target market and requirements for technical compliance. This assessment is followed by development of supportive performance data and demonstration projects. From this initial design guidance can be assembled and disseminated. Uptake should be driven by effective marketing, and performance and design guidance must be persistently reviewed and revised. The authors demonstrate this through a case study of an advanced composite decking system. Whilst the authors place an emphasis on the provision of material information to designers as a key means of promoting sustainable material choices, even in cases where sufficient information and demonstration projects are available, material choices are typically governed by other priorities. An international study of design teams conducted in 2012 by Arup for the WBCSD demonstrated that, although a large number of factors influence material choice, cost was the overarching priority and material sustainability criteria were often less influential than the personal knowledge and past experiences of the project team (Arup & WBCSD, 2012).

The literature review described in Section 4.2, encountered an array of barriers, presented in Table 11. Whilst the review considered a diverse range of materials, it is clear that they share many common barriers. In practice, the suitability and sustainability of a particular material is highly dependent on site and project-specific factors. The lowest embodied carbon solution will vary across structure types and from project to project. The end goal of policy makers and advocates of low carbon construction must be to promote the most appropriate option for each particular project. Therefore simultaneous promotion of a wide variety of material options is essential. This requires skills development and legislation that is sensitive to, and supportive of, this multitude of options. Therefore, whilst it is crucial for focussed studies to assess the barriers to adoption of particular materials, it is also essential to identify the leverage points and interventions that can overcome common barriers and support multiple solutions.

This broader approach was adopted by Watson et al. (2012) when conducting an online questionnaire and series of subsequent interviews assessing the barriers to entry for non-conventional building materials. Watson surveyed 62 UK construction professionals on their opinions and views of alternative materials, how often these materials are used and what influences their use. Results demonstrated that awareness of many alternative materials such as rammed earth, CLT and straw bale infill was high, but use remained low. Over half of respondents had not considered using non-conventional materials and less than ten had practical experience. Respondents believed that architects had the greatest influence on material choice (though the respondent demographics featured a strong bias towards structural engineers). The principal barriers identified were high costs, lack of technical knowledge and lack of client knowledge.

Jones et al. (2015) further explored the underlying barriers to the adoption of novel materials in the UK construction industry through an empirical study of the adoption of CLT. (It should be noted that this study was conducted at the same time as the survey and interviews presented later in this chapter). The study featured a survey of 49 construction practitioners (of which 70% were architects), followed by 8 semi-structured interviews. 27 of the survey respondents had experience using

Table 11: Common barriers to the uptake of low carbon building materials

Institutional and habitual	Economic	Technical and performance-related	Knowledge and perceptions
Institutional culture and established practice promotes preferred material palette	High cost of new products	Lack of established standards, design guides and tools, and standardised details	Lack of awareness and practical knowledge of alternatives amongst practitioners
Focussed training and recruitment results in departmental lock in to familiar materials	Market externalises cost of embedded emissions	Lack of material performance data	Lack of client knowledge of alternatives
Time constraints prevent consideration of alternatives and favour familiar designs	Uncertainty premium placed on novel products	Lack of full-scale demonstration projects	Negative perceptions amongst practitioners
Lack of established advocacy groups for alternatives	High transaction costs of additional professional training and research	Policy and regulatory limitations and restrictions	Negative perceptions held by clients
Lack of effective marketing from material producers	Money sunk in existing materials (in terms of training, establishing relations with supply chains etc.)	Lack of confidence in contractor ability and availability of skilled labour prevents inclusion in design	Insufficient fit with the culture of the clients or end users
Lack of user-producer relationships	Lower design:fee ratio because of increased detailing	Shortage of specialist skills prevents installation	Perceived unreliability or risk of new alternatives
Habitual specification and historic practice of individual practitioners	Insufficient comparative information on costs	Insufficiently developed supply chains	Perceived concerns about material sourcing prevent selection
Material selection viewed as outwith influence of individual practitioner	Unwillingness to accept associated financial risk	Local availability of materials and technologies	Policy uncertainty
High level of design inconvenience	Access to finance for SMEs	Difficulty obtaining insurance for novel and reused materials	Simply regarded as low priority and other considerations take precedence
Lack of supply chain coordination	Project financing incompatible with time constraints		
	Anticipated increase in lead times		
	Small industries producing alternatives cannot compete against established industries' economies of scale		

CLT, whilst a further 7 had considered use but were unable to get the material adopted. Concerns over risks to project costs and unfamiliarity with the product were identified as the two key barriers. Projects that achieved successful CLT adoption were typically low value (<£5m), for non-commercial clients, and featured proposals for CLT use by designers at the early project stages. The single greatest driver of CLT adoption was 'client concerns for the environment', which were cited in 29.4% of adoption cases. However, in many instances, CLT was selected to meet unique project requirements, such as site constraints, with the associated sustainability benefits a secondary concern. This led the authors to conclude that "*unique project contexts formed by client values and experience, site constraints, or planning and regulatory requirements, create niche-like environments with conditions which might not be satisfied by dominant technologies, requiring an alternative approach to construction… understanding and exploiting these niche conditions is key to successful deployment of unconventional approaches*." Precedents from the field of innovation studies describe how such technologies can exploit niches before emerging through 'windows of opportunity' to change overarching socio-technical regimes and break existing industry path dependencies (e.g. Geels, 2004).

Ariyaratne and Moncaster (2014) considered the approach of designers to embodied carbon assessment and mitigation through a survey of 37 industry practitioners and 6 expert interviews. Whilst the survey principally focussed upon embodied carbon assessment tools, it also highlighted some of the common barriers to low carbon design and material selection. In practice many of the most important design decisions were made prior to any environmental performance analysis. The authors observed that this "*lack of early integration of sustainability assessments into the design process leads to extensive modifications being required at later stages to meet the performance criteria*." This prevents inclusion of certain alternatives and increases the cost of others. These problems were compounded by a dependence upon "*experience and…tried and tested methods*". Designers also experienced difficulties presenting the value of carbon assessment to clients, particularly in the current economic climate. The authors identified "*that under most circumstances, it was unclear how the environmental impact assessment of designs are being carried out or who was taking the responsibility for carbon reduction. There was a certain sense of passing the responsibility to another discipline, particularly towards sustainability consultants.*" The authors argued that overcoming this problem will require clear allocation of responsibility and "*a new-breed of designers with the right set of skills and approach*." The authors argued that "*from a designer's point of view, developing low embodied carbon designs could be considered as a state of mind. It is the cultural awareness that needs to be bred into the designers in a similar manner to how the awareness of health and safety was raised within the industry.*"

The three general studies highlighted here, and the numerous studies of specific materials, exhibit a number of recurrent themes. Namely: the lack of early engagement of certain project professions; a failure to consider embodied carbon in early project stages; a shortage in knowledge and skills amongst designers; negative perceptions of alternative materials; ineffective allocation of responsibility amongst project participants; and the fundamental lack of drivers for adoption of innovative low carbon solutions. The survey and interviews presented in the remainder of this chapter explore these barriers in greater depth and consider potential drivers for adoption of low carbon materials.

5.3 Research methodology, objectives and boundaries

The overarching objective of this chapter is to understand the cultural, behavioural, and perceptual barriers to adoption of alternative low carbon building materials amongst industry practitioners involved in design, specification and construction. The preceding literature review highlighted the range of economic, technical, practical and cultural barriers preventing construction professionals from selecting materials commonly identified as being lower in embodied carbon. The following survey and interviews explore these barriers in greater depth than prior studies and consider the role for regulation, professional institutions and advocacy groups in overcoming these barriers. The following paragraphs set out the approach and study boundaries and explain the respective survey and interview methodologies.

5.3.1 Boundaries

Despite the recent growth in understanding, embodied carbon remains a niche topic within the construction industry. Therefore the surveys and interviews did not seek to recruit participants that would constitute a representative sample of the UK construction industry at large; but rather targeted individuals with extensive experience of using low carbon materials. The UK represents a global leader in this field, and UK construction practice is widely emulated throughout the world. The vast volume of overseas project work conducted by UK practitioners based within multinational firms contributes to an international spread of British construction practice. This is supported by the common international use of British and European standards and environmental assessment methods, such as BREEAM. Thus understanding the views and experiences of early adopters in the UK is crucial, as these early adopters will ultimately shape both domestic and global practice. Understanding their motivations and experiences is informative in developing appropriate regulatory strategies and guidance for the broader industry.

Construction industry supply chains are typically lengthy and complex, involving a variety of professions. Many of these actors have fundamentally different motivations and priorities. In this study an attempt was made to limit participants to professionals involved in the design, specification and construction process. Professionals involved in these disciplines have previously been the subject of various studies assessing general barriers to sustainable and green building but their views relating to embodied carbon and materials had not previously been comprehensively addressed. The survey and interviews were not targeted at developers, end-users or material manufacturers. Further specific studies that focus on the perspectives of these groups would be valuable additions to the research field.

5.3.2 Overarching approach

The initial assessment of barriers to the adoption of low carbon materials is derived from the literature review already detailed. This initial compilation of barriers became the subject of further research which adopted a mixed method approach combining a survey and series of semi-structured interviews. A sequential explanatory approach was selected, whereby a survey would gather initial quantitative and qualitative data on the barriers to adoption, followed by interviews exploring the identified barriers in greater depth. This approach is commonly used across a range of disciplines (see Tashakkori & Teddlie (2003)) and was selected to provide the desired combination of breadth and depth.

5.3.3 Survey methodology

An open online questionnaire was hosted using Qualtrics and made available from 03/04/14 to 23/05/14. An open online questionnaire was deemed the most appropriate format as it provided the means for practitioners to easily share the survey and maximise the number and range of responses. Links to the survey were distributed through a number of major industry mailing lists, established contacts, LinkedIn groups and to a targeted set of individuals with extensive experience of using low carbon materials. Flyers with a survey link were also distributed at events during the UKGBC Embodied Carbon Week (07/04/14-11/04/14). Participants were encouraged to pass on the link to colleagues and contacts. Owing to the self-selection process, the sample of respondents is predominantly constituted of industry practitioners with an active interest in the topic and experience using the range of materials discussed. The sample is not reflective of the broader industry but provides an insight into the motivations and experiences of those early adopters who already have experience using a range of less common materials. The limitations of the survey sample are discussed further in Section 5.7.

The survey was designed using a mix of open and closed questions. In all instances where respondents were asked to choose from a prescribed list the opportunity to add other options and provide comments was made available. The survey featured 17 core questions (see Table 12) with additional piped questions depending upon the participant's response. A full list of questions and all possible responses can be found in Appendix C. The core questions focussed on gathering demographic data; establishing the perceived influence and responsibility of respective professions on material selection and embodied carbon reduction; gathering respondents' experiences with a range of 24 example low carbon materials; and exploring perceived barriers and drivers to the adoption of low carbon materials.

The 24 example materials were selected to provide a range of both novel and traditional products. This included materials developed from natural sources; materials incorporating waste streams or recycled content and products optimised through novel production techniques. The materials were selected from a long list developed through the literature review, with preference given to materials included in prior qualitative studies to allow for comparison of results. The final 24 materials included were: Brettstapel; Cross Laminated Timber (CLT); Structural Insulated Panels (SIPs); straw bale (either load bearing, infill or modular); rammed earth; unfired brick; cob; adobe; hemp (including hemp-lime composites); limecrete; cardboard (tubes or panels); Ethylene Tetrafluoroethylene (ETFE); inorganic Fibre Reinforced Polymers (FRP); geopolymer concrete; concrete containing agricultural wastes (e.g. rice husks, vegetable fibres or nut shells); concrete containing consumer wastes (e.g. plastics,

Table 12: Survey questions

1. What is your job title?
2. What is the typical project role of your employer?
3. In which country do you normally work?
4. For how many years have you worked in construction?
5. Approximately how many staff does your company directly employ?
6. How much influence do you have over the selection of materials and construction products on a typical project?
7. Who do you believe has the greatest influence over material and construction product selection on a typical project?
8. Please rank who you believe should ultimately be responsible for minimising the embodied carbon emissions on a project.
9. What is your knowledge of the following materials and construction products?
10. How often have you used each of these materials?
11. How would you rate your experience of using each of these materials?
12. Thinking about the projects on which you used these materials. Why did you choose to use each material?
13. Would you use these materials again? / Why would you not consider using these materials again?
14. You stated that you are aware of but have not used the following materials on a project. Why have you chosen not to use these materials?
15. Thinking more generally about alternative materials in construction, how important do you believe the following factors are in preventing their use?
16. How important do you believe the following developments could be in encouraging greater use of alternative materials and construction products?
17. Is there anything else you would like to add about any of the topics discussed?

glass or tyres); concrete containing construction and demolition wastes; concrete containing industrial wastes (e.g. steel slag, sewage sludge ash, silica fume); precast hollowcore floor slabs; optimised roll-out reinforcement meshes (e.g. BAMTEC or ROLLMAT); recycled aggregates; recycled plastic lumber; reclaimed steel; and reclaimed timber. This does not constitute a comprehensive list of all low carbon materials available in the construction marketplace. Such a list would be too lengthy for inclusion in a short survey and would likely reduce the survey completion rate.

Respondents were initially asked to describe their knowledge and experience of each of the 24 materials by selecting from 3 options: 'used on project(s)'; 'aware of but not used'; or 'little or no knowledge of'. Questions 10-14 were then filtered to gather respondents' experiences with each of the materials that they had used, and reasons for not selecting materials they had not used. Following the questions about specific materials, respondents were asked to consider more general barriers and drivers to alternative materials. The survey was structured in this form to allow comparison between the specific experiences of practitioners that had used each material with the perceptions and barriers reported by practitioners that were not using that material. This was a deliberate attempt to help distinguish potential perceptual barriers.

Following an initial draft, survey questions were reviewed by an independent academic with extensive experience conducting industrial surveys. A revised version was then tested and further refined based on responses from a pilot group of architects and engineers. Following minor amendments, a final round of sit in testing was done to ensure full understanding of the questions, prior to distribution.

5.3.4 Interviews methodology

All survey participants were asked if they were willing to take part in a follow up interview exploring the topic in greater depth. 24 out of 47 respondents indicated a willingness to do so and provided contact details. Survey participants demonstrating particular experience were selected for a short series of in depth

Table 13: Interviewees

Position	Type of Organisation
Sustainability Manager	Multinational contractor
Senior Engineer	Large multidisciplinary consultancy
Architectural Technologist	Specialist architectural practice
Director of Sustainability	Professional institution
Assistant Head of Sustainability	Large client
Sustainability and LCA Expert	Research technology organisation
Founder	Sustainable Business Partnership and Chair of Embodied Carbon Task Force

interviews. Additional interviewees representing specific professions or industry bodies were also sought to provide an appropriate breadth of expertise.

The interviews were semi-structured and typically of an hour in length. All interviews were conducted face to face and recorded for transcription. A common set of questions and prompts were prepared, tested and refined through a test interview. These common questions were designed to build upon responses from the survey. Additional questions specific to the experiences of each interviewee were also prepared to maximise the quality of responses. All interviewees were offered anonymity, which some declined. A full list of interviewees can be seen in Table 13. Recordings were transcribed, coded and subjected to thematic analysis. This was conducted in the common software package NVivo 10. Open coding was used to identify salient issues from the interview transcriptions. Axial coding was then used to extract the key distinctive and recurrent themes. The discussion of results is framed by these themes.

The following sections present results from the survey and interviews in turn. The subsequent discussion draws results together and provides a number of recommendations.

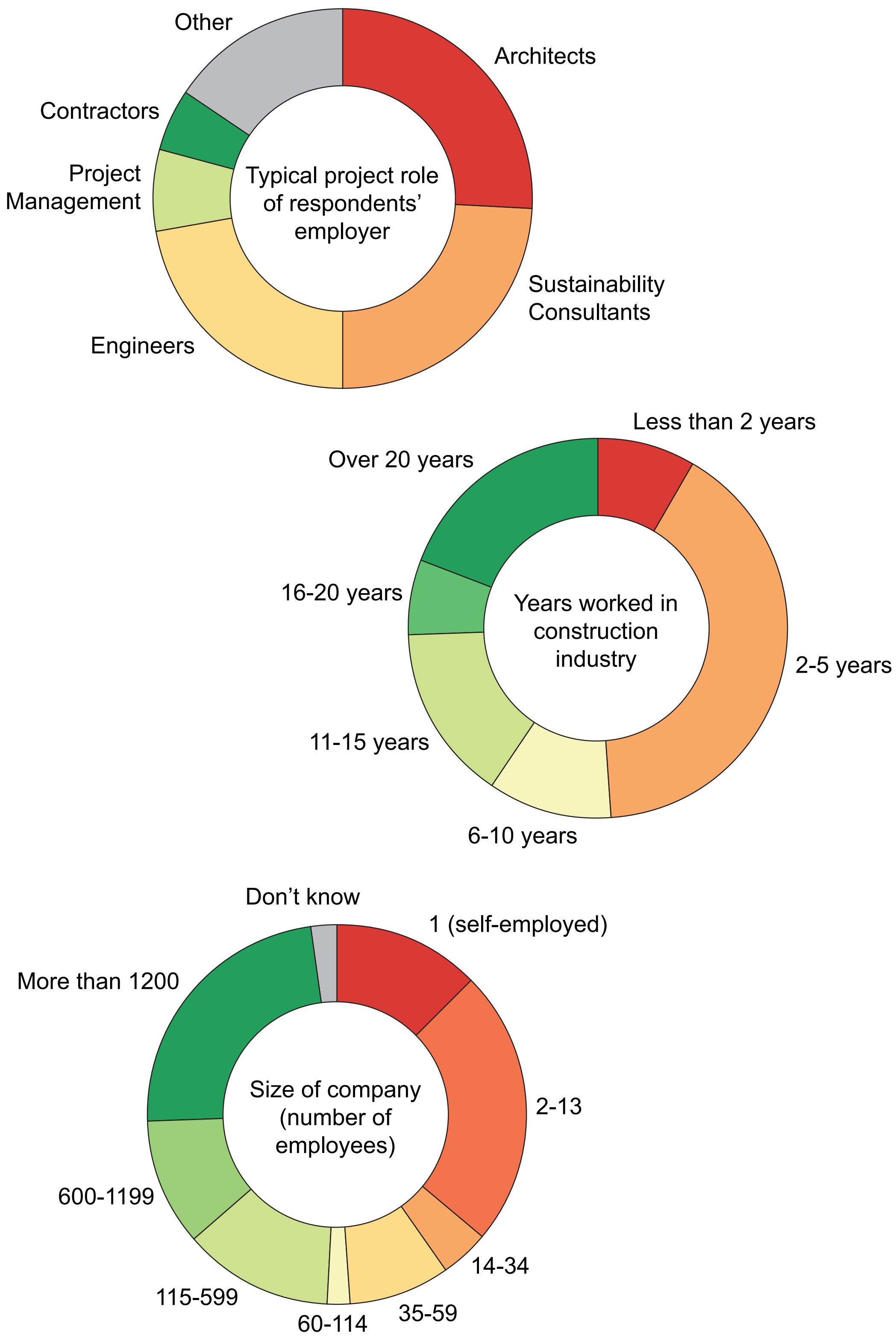
5.4 Survey results

The following section presents a summary of key survey results. The results should be read with due caveats on the limitations of the working sample and constrained scope of research, as outlined in Section 5.7. Full tables of results can be found in Appendix C.

5.4.1 Demographics

The survey received 32 full responses and 15 partial responses that provided answers to the majority of the questions. A further 37 incomplete responses, where respondents had only answered a small number of questions (typically Q1-8), were omitted from results. These respondents presumably failed to complete the survey owing to excessive survey length or lack of interest. The average survey completion time was 16 minutes, with the longest taking 50 minutes. An overview of the respondent demographics can be seen in Figure 14. The majority of respondents were architects, engineers and sustainability consultants. A small number of responses were received from contractors and project managers. 'Other' professionals were involved with research, development, trade associations or construction product manufacture and supply. 77% of respondents worked primarily in the UK, the remainder worked in other mostly developed countries (Australia, Colombia, Denmark, Greece, Hong Kong, Hungary, Ireland, Romania, Spain and USA). Most EU countries plus Australia, USA and Hong Kong have similar drivers and comparable assessment schemes for sustainable construction and share many common practices with the UK industry. For this reason it was considered suitable to include their responses in one sample with UK respondents. Across the sample, respondents exhibited a range of experience with 40% of respondents having worked for 11+ years in the industry. Respondents were well distributed across companies of different size (in this case measured by number of employees).

Figure 14: Survey respondent demographics



5.4.2 Influence and responsibility of respective professions

Survey respondents were initially asked about their own influence on material and construction product selection. Most respondents felt they had at least some influence, with architects the most likely to report a strong or primary influence (see Figure 15). Respondents were then asked to consider the influence of the respective professions. Respondents generally reported that the architect, client, civil/structural engineer and contractor had the greatest influence over material and construction product selection (see Figure 16). Whilst some minor variation in these results exists when broken down by the respondents' profession, the architect, client, civil/structural engineer and contractor consistently remain the principal influences. These results are consistent with those from Watson et al. (2012) and the Arup study (Arup & WBCSD, 2012).

Respondents were then asked to consider the professions that should be most responsible for ensuring embodied carbon reduction on a project. Responses across all professions indicate that the architect should be the professional most responsible for minimising embodied carbon on a project (see Figure 17). Civil/structural engineers, the client and sustainability consultants also have a key role to play, and were consistently ranked higher than the remaining professions. It is clear when comparing Figure 16 and Figure 17 that the professions identified as having the greatest influence over material and construction product selection are also those that respondents believe should bear the greatest responsibility for minimising embodied carbon emissions.

Figure 15: Perceived influence of respondents on material and product selection *(Response to survey question: How much influence do you have over the selection of materials and construction products on a typical project?)*

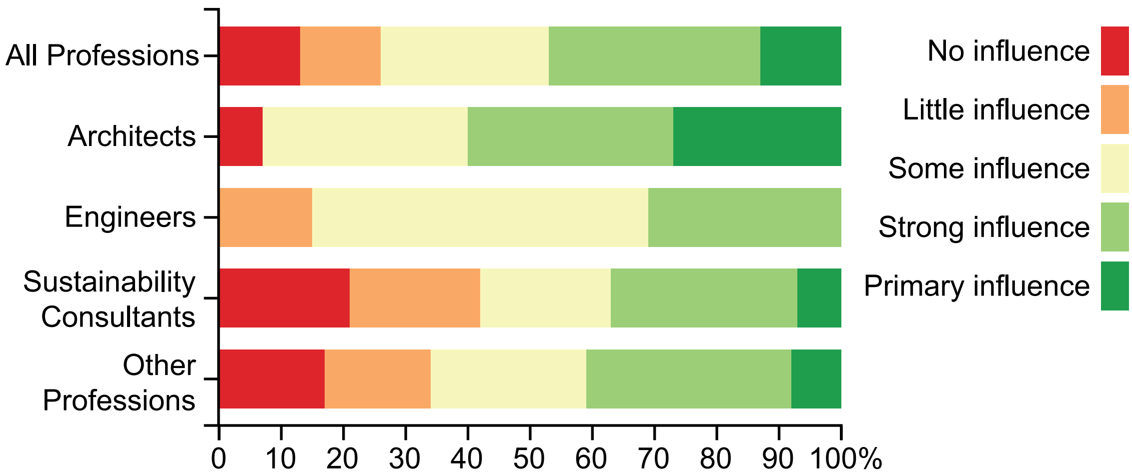


Figure 16: Influence of professions on material and construction product selection *(Response to survey question: Who do you believe has the greatest influence over material and construction product selection on a typical project?)*

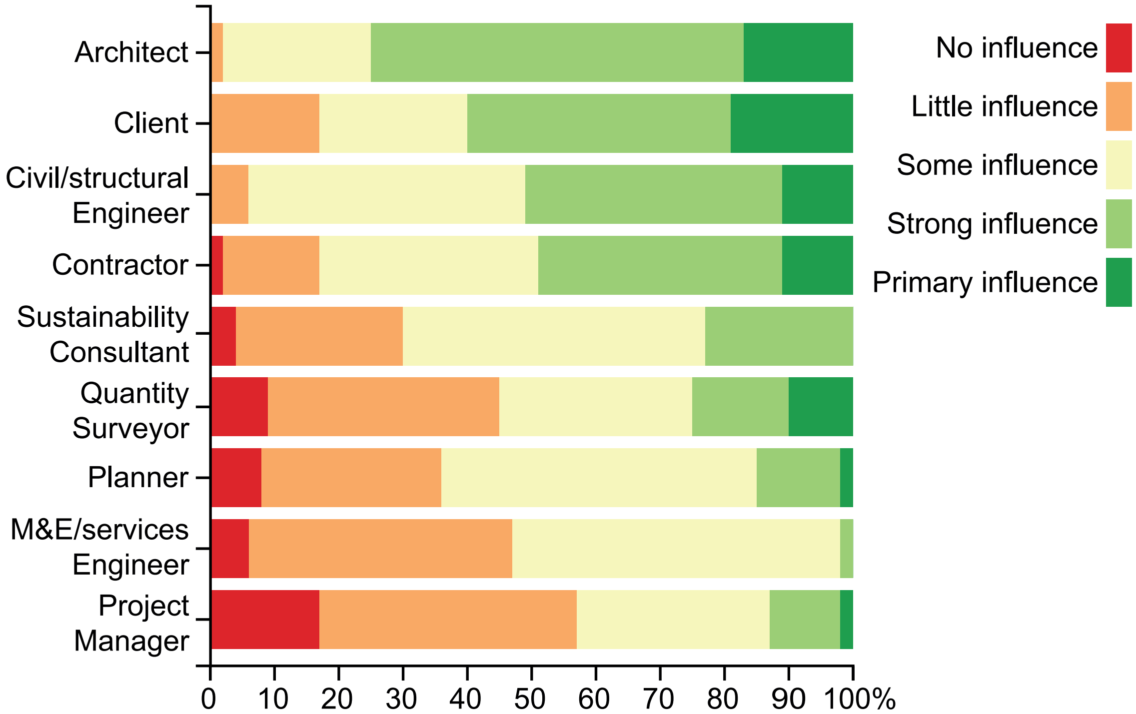
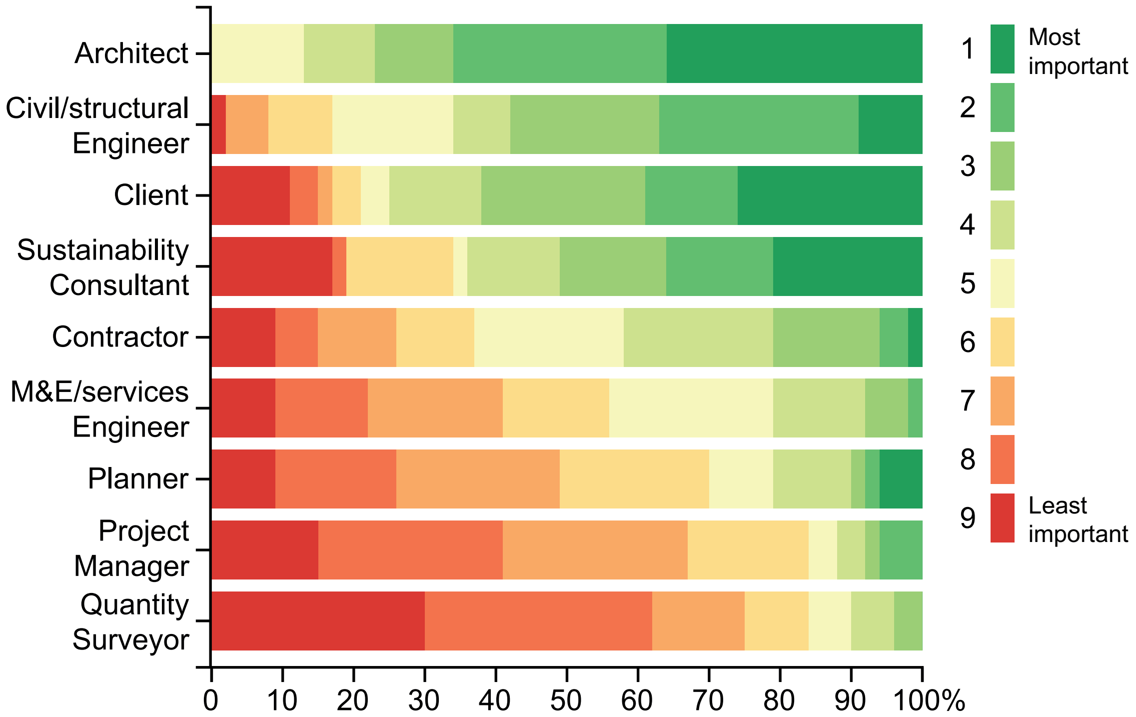


Figure 17: Professions believed to be most responsible for embodied carbon reduction *(Response to survey question: Please rank who you believe should ultimately be responsible for minimising the embodied carbon emissions on a project.)*



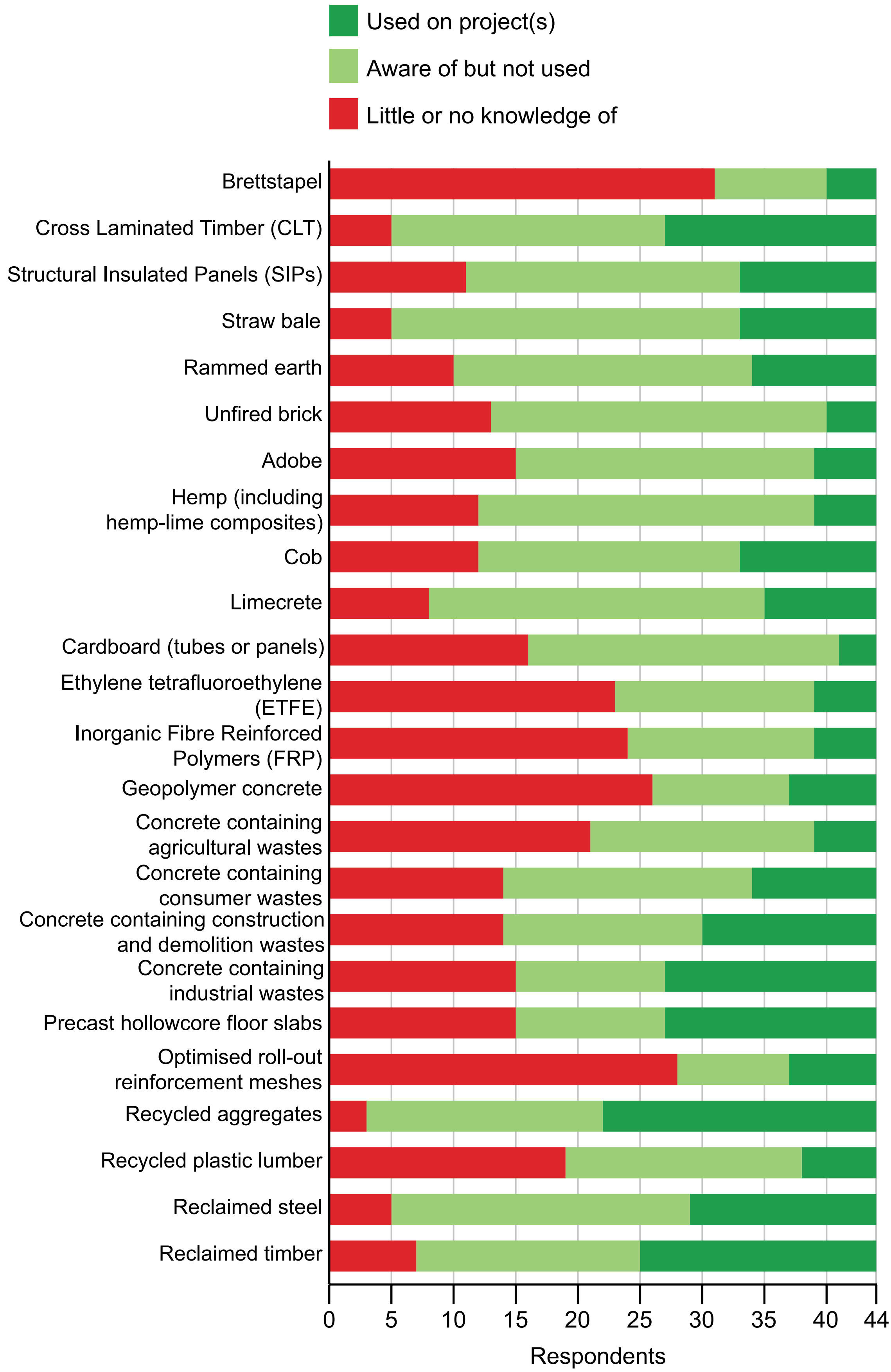
5.4.3 Knowledge of alternative materials

Respondents exhibited a broad range of awareness and experience with the materials included in the survey (see Figure 18 overleaf). Each material had been used by between 3 and 22 respondents on at least one project. The most commonly 'used on projects' were CLT, recycled aggregates, precast hollowcore floor slabs, reclaimed timber, reclaimed steel and concrete containing industrial wastes. Straw bale, unfired brick, adobe and limecrete were the most commonly 'aware of but not used'. Brettstapel, optimised roll-out reinforcement meshes, and geopolymer concrete reported the highest rates of 'little or no knowledge of'. This is unsurprising as these are relatively novel products. When results were broken down by respondents' professions, sustainability consultants reported the highest proportion of 'used on project(s)' across a range of materials, and also the lowest rates of 'little or no knowledge of'. This may suggest that they possess a broader knowledge and experience working with a range of low carbon materials. This is in spite of the participating sustainability consultants, on average, having fewer years of industry experience than respondents from other professions. Amongst all respondents, reclaimed materials and alternative concretes were more likely to be routinely considered for use on a project than natural or unconventional materials.

5.4.4 Experiences with alternative materials

Survey respondents were asked to reflect on their experiences with materials they had used; many provided detailed comments. Across all materials, 65% of reported experiences were somewhat or mostly positive. No respondents reported a mostly negative experience and only 7% of experiences were somewhat negative. 90% of professionals that had only used a material on one project would use the material again. This high rate of positive experiences may reflect a sample bias inherent in the self-selection process for survey participants. Those with positive experiences of alternative materials are perhaps more likely to participate in such a survey. Alternately, it could simply reflect generally positive experiences amongst those practitioners that have adopted alternative materials. Those that reported negative experiences with materials, or stated that they would not consider using a material again, generally expressed concerns about high costs, inadequate performance, inconsistent quality, lengthy construction times or difficulty sourcing product at scale. Further examples included respondents suggesting that SIPs are "*inflexible for accommodating late changes*", Brettstapel was often "*not very dimensionally stable*", and recycled steel suffered from "*clients concerned over warranty and liability*". Some comments referred to unwillingness from other professions to utilise certain materials due to "*preconceptions and inexperience*". However, the bulk of comments were positive or specified the circumstances in which the particular material was preferable.

Figure 18: Knowledge of example materials *(Response to survey question: What is your knowledge of the following materials and construction products?)*

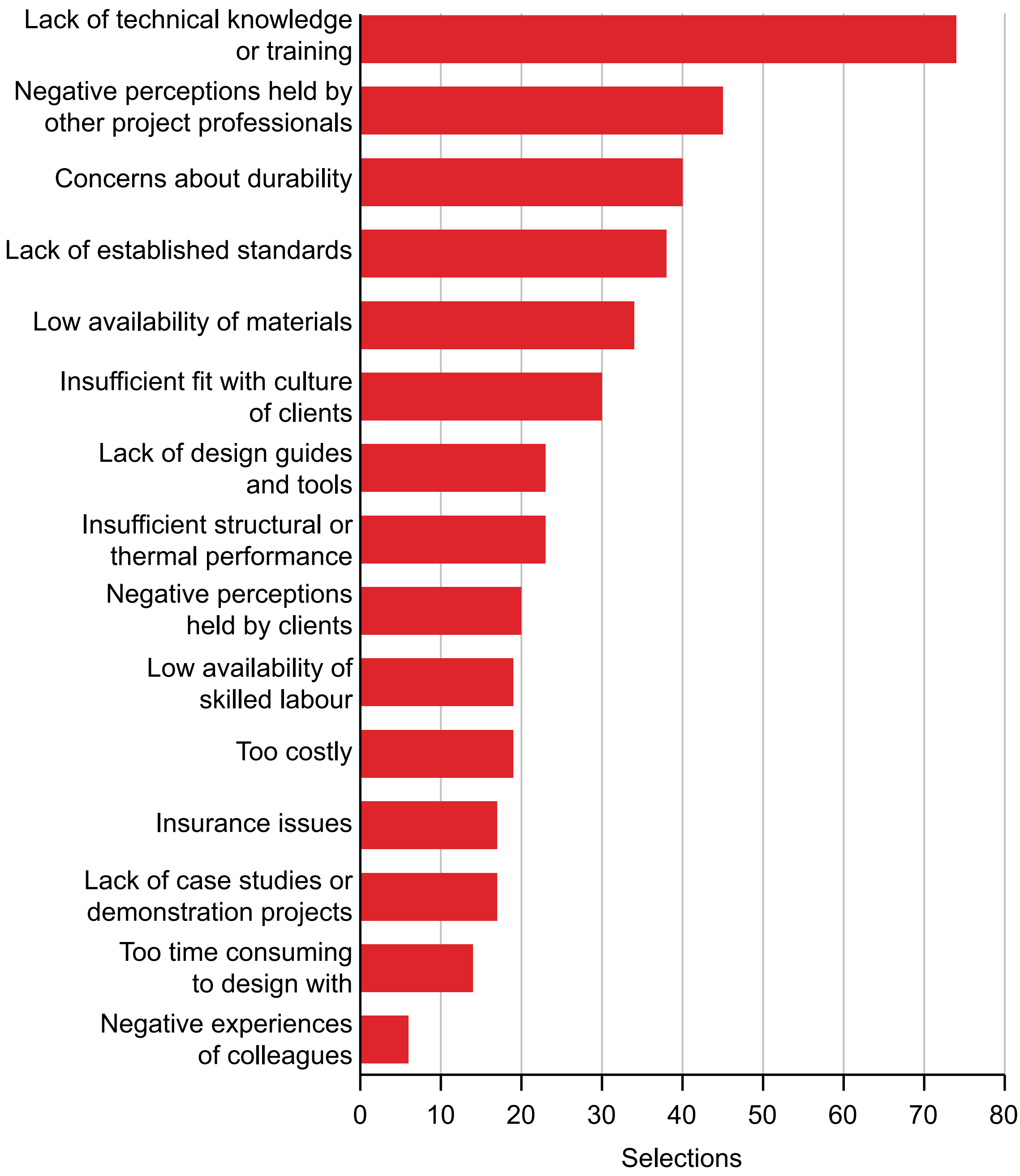


5.4.5 Barriers

Participants were questioned on the barriers preventing their use of the specific example materials (see Figure 19) and also on the barriers to alternative materials in construction in general terms (see Figure 20 overleaf).

Lack of design knowledge and skills was repeatedly identified as a major barrier and numerous respondents commented that they would like to know more about a number of the example materials. Few reported 'negative experiences of colleagues' as a barrier, and no respondents reported a mostly negative experience themselves using any of the example materials. However, many cited 'negative perceptions' as a

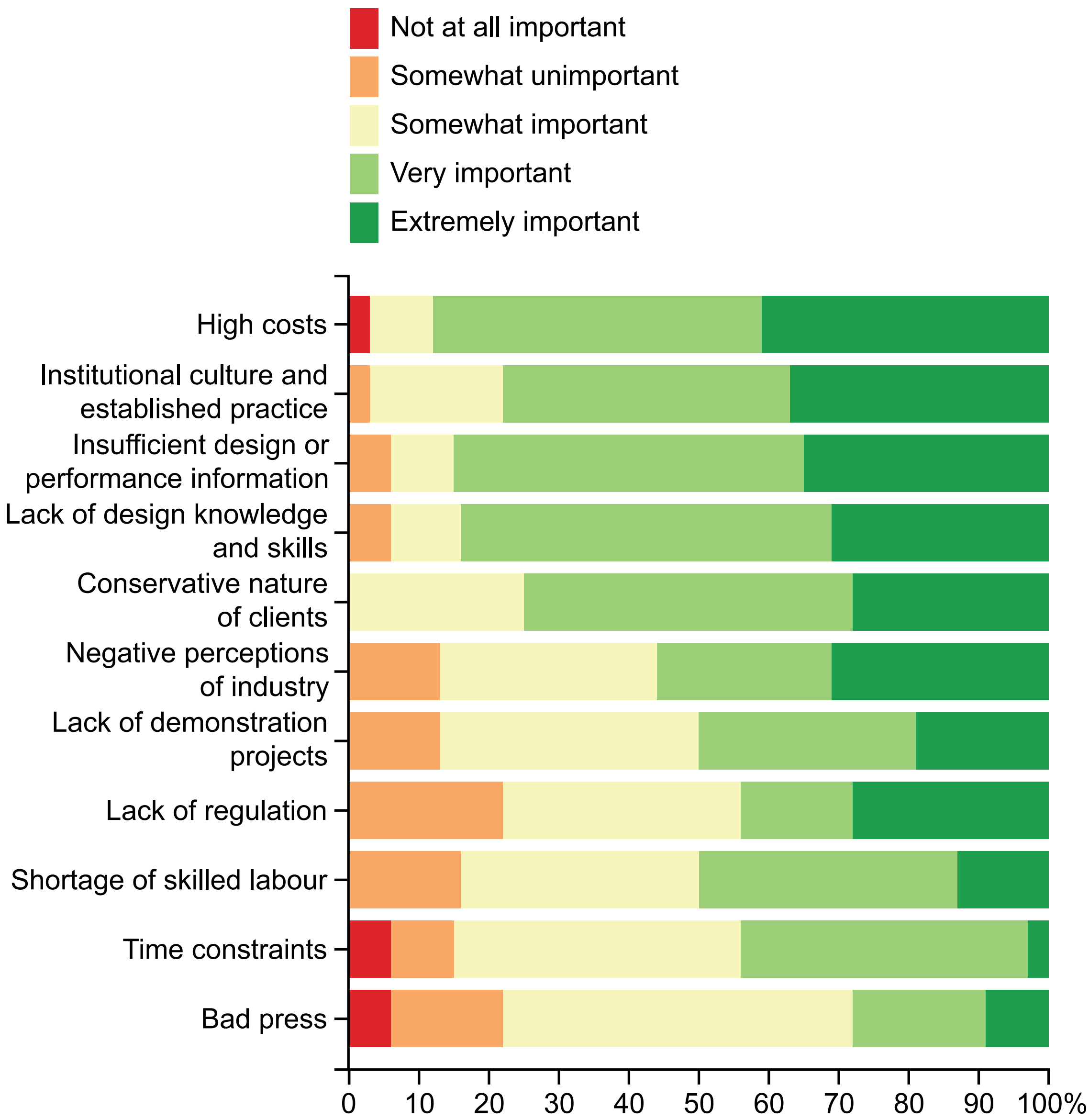
Figure 19: Barriers to use of the example materials *(Aggregated responses to survey question: You stated that you are aware of but have not used the following materials on a project. Why have you chosen not to use these materials?)*



strong barrier. This may suggest that perceptions rather than experiences currently prevent selection of alternative materials.

When discussed in general terms, high costs were deemed the greatest barrier to low carbon materials. This is unsurprising, as clearly stated by a responding UK architect - "*on most construction projects, cost is still the major driver*". However, when specifically questioned on the 24 example materials, few respondents selected cost as a barrier preventing use. This suggests that the perception of high cost may be an important barrier in itself. This is a common barrier to sustainable building in general, and one that recent industry studies have sought to challenge (e.g. Abdul & Quartermaine, 2014).

Figure 20: General barriers to use of alternative materials *(Response to survey question: Thinking more generally about alternative materials in construction, how important do you believe the following factors are in preventing their use?)*

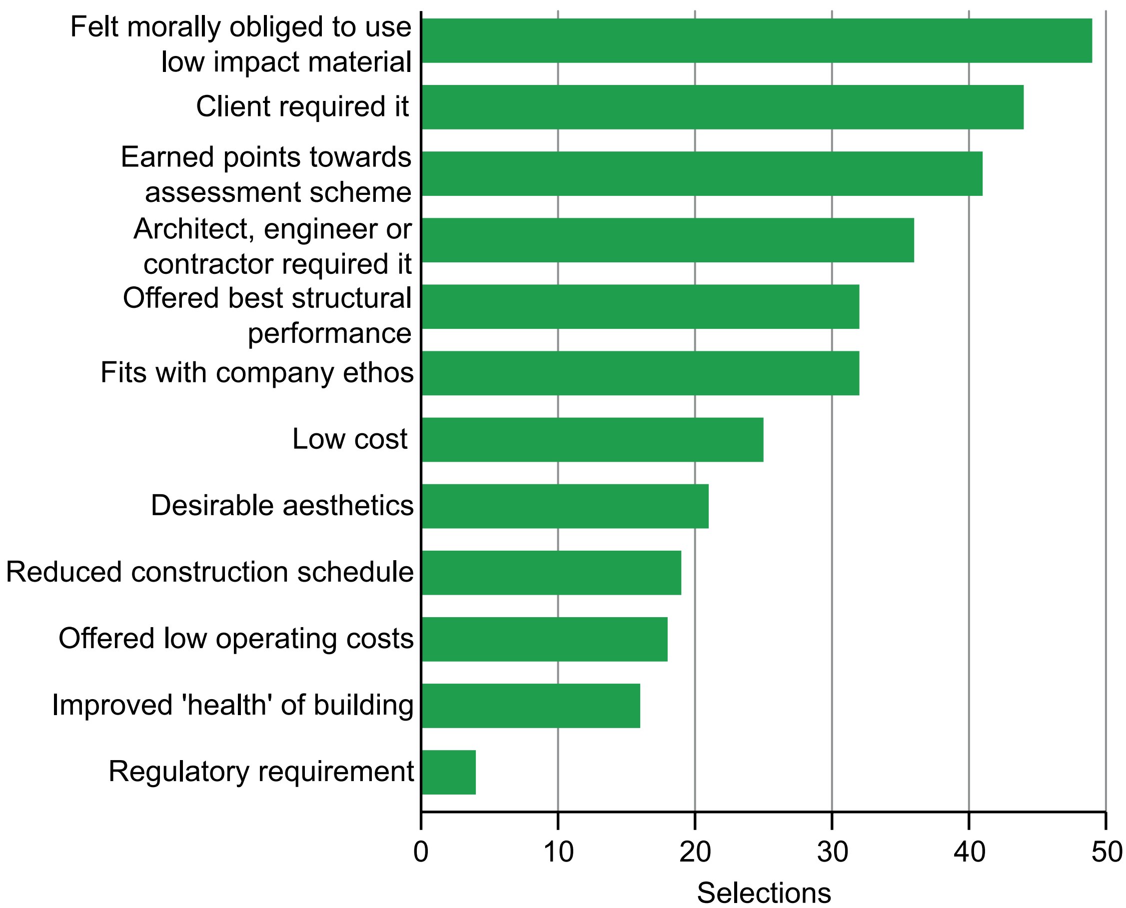


Institutional culture and the conservative nature of clients were also identified as key barriers, alongside concerns about durability, lack of established standards and low availability of materials. In contrast, time constraints, lack of demonstration projects and availability of skilled labour were infrequently cited. 'Negative perceptions held by clients' and 'negative perceptions held by other project professionals' were more commonly selected for natural materials such as straw bale, rammed earth, cob and adobe. Meanwhile 'low availability of materials' was the most commonly selected barrier for reclaimed materials. Some comments highlighted the respondents' desire to use an alternative material being prevented by another practitioner. For example, one architect discussing CLT observed that *"Tried to use on many projects, often with support of structural engineer - over ruled on cost grounds by QS"*.

5.4.6 Drivers

When respondents were asked specifically about their reasons for selecting the example materials, the most commonly reported reasons were: 'felt morally obliged to use low impact material' and 'client required it' (see Figure 21). This supports the finding of Persson and Grönkvist (2014) that the personal convictions

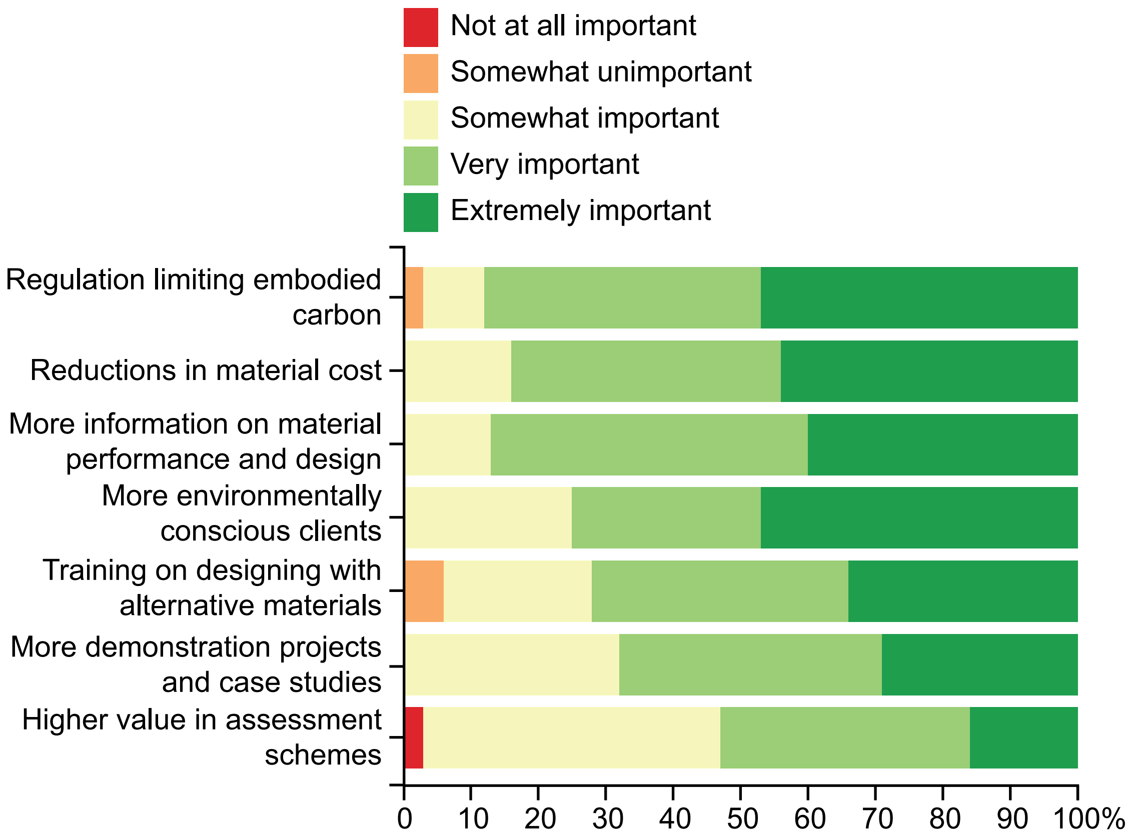
Figure 21: Current drivers of use of the example materials *(Aggregated response to survey question: Thinking about the projects on which you used these materials. Why did you choose to use each material?)*



of individuals are a strong driver of low carbon construction. This suggests that changing motivations of clients and construction professionals could drive demand for low carbon materials in the short term. 'Client required it' was a particularly common factor for natural materials such as hemp and straw bale. Whereas 'felt morally obliged to use low impact material' was a factor across a range of materials. 'Earned points towards assessment scheme' (such as BREEAM) was also frequently selected, mostly for recycled and reclaimed materials, as well as CLT.

When asked in general terms about future drivers, 88% of respondents stated that 'regulation limiting embodied carbon in construction' was either very important or extremely important in encouraging greater use of alternative materials and construction products (see Figure 22). Reductions in material cost and more information on material performance and design were also identified by over 80% of respondents as being very or extremely important. Perhaps surprisingly, higher value in assessment schemes (such as BREEAM and LEED) was the least popular potential driver. One architect commented that "*fewer clients seem to be demanding BREEAM than before the recession*" – suggesting that a downturn in demand would limit the effectiveness of any assessment scheme changes. Future rises in energy costs were also identified as a potential driver by multiple respondents.

Figure 22: Future drivers of alternative material use *(Response to survey question: How important do you believe the following developments could be in encouraging greater use of alternative materials and construction products?)*



5.4.7 Other comments

Many respondents expressed a concern about the lack of consistent and comparable methods of calculating and reporting embodied carbon. For instance one designer complained that embodied carbon calculators and LCA tools "*are poorly understood, rarely used and often grossly inaccurate in the UK*". This is compounded by dependence on generic LCI data sources, such as the ICE inventory (Hammond & Jones, 2008), which was criticised as "*the methodology is an absolute shambles*". The LCA treatment of carbon storage in biogenic materials was also subject to debate.

Several respondents noted a definitive lack of enthusiasm for change amongst their colleagues. Some expressed a concern that a persistent industry focus on technological solutions that reduce operational emissions is making it harder to engage clients and other professionals on material issues. For instance one architect noted that "*the prevalence of eco-bling in the form of renewable energy harnessing gadgets and gizmos take all the headlines, which perpetuates the idea that the materials you make a building from don't matter if you plonk a solar panel, wind turbine or the dreaded heat pumps on to it*".

An interesting point was also raised by the Head of Sustainability for a contractor working in the fit out sector: "*fit out projects are much smaller than shell & core, but there are very many more of them. There remains a case to be made to make carbon accounting on such small projects both time and commercially viable for clients and their project team*." It could be argued that this challenge of making small scale assessments viable underscores the need for a range of basic assessment tools and one common accessible data source.

A further respondent expressed a concern that low carbon materials are typically grouped together and discounted as a whole by the industry as a "*hippy fad*". Such generalized negative perceptions of a diverse range of materials may, in part, explain the discrepancy between the generally reported barriers to adoption of alternative materials and the experiences of practitioners with specific materials.

5.5 Interview results and discussion

All interviews were recorded and transcribed in NVivo 10. Transcriptions were then coded and subjected to thematic analysis. Select quotes populate the following discussion which draws together results from the interviews. The discussion is framed by the core themes that emerged from the analysis, and in some instances, refers back to the survey results which were revisited during analysis of the interview transcripts. The core themes are summarised in Table 14 overleaf.

Before discussing these barriers and drivers, it is important to note the interviewees attitudes towards carbon reduction. The interviewees generally agreed that the construction sector should be aiming for an 80% reduction in emissions – consistent with UK targets – and did not deserve any special dispensations compared with other sectors responsible for substantial emissions, such as transport. However, all interviewees, except one, believed such a target was unlikely to be achieved. In spite of this they saw value in the targets setting out a broader aim and principal, and providing an example to other nations. On a day to day level, interviewees preferred to approach the problem in terms of actions not numbers. Interviewees also believed that radical not incremental change is needed to even approach the targets; and that an increased focus on embodied carbon would be a key component of this. Interviewees believed fundamental changes in end user and industry attitudes and the introduction of regulatory requirements will be essential in driving this change.

"I think there has to be a huge shift in how people live not just how we build, and how people interact with those buildings, to get anywhere near 80%."

Architectural Technologist – Specialist architectural practice

"I know we have set these targets of 80% reduction, that's linked to science and what we believe needs to happen…but I tend to try not to think too much about the numbers and more about the actions. I don't know if maybe that side of the Routemap has been lost a little bit."

Sustainability Manager – Multinational contractor

Table 14: Interview themes

Thesis section	Themes
5.5.1 Barriers	Allocation of responsibility for embodied carbon reduction Availability of data and product information Industry culture Costs Low value of materials Knowledge, understanding and skills Demonstration projects and product testing Early engagement Negative perceptions of low carbon materials
5.5.2 Drivers and opportunities	Moral convictions Establishment of an embodied carbon community Client requirements Business opportunities Regulation Building rating schemes BIM and automation
5.5.3 Other considerations	Benchmarks Role for institutions

5.5.1 Barriers

5.5.1.1 Allocation of responsibility for embodied carbon reduction

When asked to rank all professions, survey results suggested that a small number of professions (architects, clients and civil/structural engineers) should be primarily responsible for material selection and embodied carbon reduction. When asked to rank these professions, the architect was clearly identified as the profession that should be most responsible for embodied carbon reduction. However, when this topic was explored with interviewees, a more nuanced view emerged. Most interviewees stated that in practice it is hard to pin responsibility for material selection and embodied carbon reduction on one party as so many actors influence project decisions; and the principal concern should be establishing a continuous chain of responsibility to ensure solutions make it into the finished building. Some interviewees felt that were this to only be driven by one professional, there is a significant risk that solutions would be compromised by other parties. To ensure the support and active participation of all project professions, several interviewees believed that responsibility for embodied carbon reduction should not be allocated to one individual but should be motivated by collective incentives for all parties in the contract structures. This alignment of all actors along the supply chain through a chain of responsibility must be driven by the client. At a practical level, this may require that the client designate an individual on the development team to monitor embodied carbon throughout the project and hold all project professionals to account.

"There are so many actors involved in producing a building or a piece of infrastructure that it's really difficult to lay responsibility with any single part… It can't be any one person's responsibility it needs to flow right from the very start. It needs to be driven by the client… setting out quite strongly right from the beginning in their brief to their designer and then in all the tender documentation thereafter. Then that flows right from the beginning right through…from the client to the designer and then definitely the whole supply chain thereafter."

Sustainability Manager – Multinational contractor

5.5.1.2 Availability of data and product information

Interviewees complained it is still "*really really hard*" to access good quality data on embodied carbon and that they were disappointed by the quality of information received from product manufacturers, not just on embodied carbon but on performance in general. The detail and presentation of information from small manufacturers of low carbon construction products will need to improve if it is to be competitive with current market leaders. Interviewees were also critical of the growing dependence on generic LCI datasets, which were seen to encourage a thoughtless approach to embodied carbon assessment.

"A lot of people who are looking at embodied carbon are just doing it as a calculation process, and they're not really looking at 'how am I reducing real impacts' cause they are using generic data and just going 'well if I use that number compared to that number then I've made a saving' but you haven't necessarily, no, you know it's just a calculation procedure."

Sustainability Manager – Multinational contractor

Interviewees also expressed concern about the inconsistencies between datasets. Several interviewees commented that this problem was not unique to the UK, and a lack of reliable data was a problem in many international markets. Some interviewees queried why other countries were able to support more firms producing low carbon materials and speculated that this could be attributed to the dominance of a small number of large firms in the UK market. Several interviewees advocated the creation of a combined UK or EU database of EPDs and generic LCI data, similar to the French INIES (INIES, 2015). It was suggested that this platform would provide a market incentive for suppliers to produce data and compete on that basis. This increased competition could unleash innovation in the supply chain. It was also felt by many interviewees that data availability would improve substantially if legislation mandating measurement of embodied carbon was introduced.

"If we get the right sort of processes and incentives in place then we'll see an amazing amount of innovation. I think what's interesting about the construction industry as a whole, is that, whilst there are a lot of embedded ways of doings things - there's a lot of inertia - when the right incentives come around then there is a lot of innovation. I think we'll see massive innovation especially amongst the supply chain…suppliers want to be better than the next door supplier because they'll get the job."

Chair of Embodied Carbon Task Force

Interviewees noted that, despite a growing willingness amongst the industry to collaborate, a change in mind-set is still needed to overcome the protective attitude towards embodied carbon data and calculation methods. The process of undertaking a carbon calculation is not especially complicated and should not be viewed as specialist knowledge. The specialist knowledge of commercial value and perhaps requiring protection should reside in the corresponding measures to reduce embodied carbon.

5.5.1.3 Industry culture

A strong resistance from other project professionals was noted in the survey and confirmed anecdotally by the interviewees. Interviewees stressed that individual practitioners are not inherently neophobic and the unwillingness to adopt unfamiliar materials is largely a consequence of the risk-averse and litigious culture that pervades the industry. Where innovations are seen as convenient, or liability rests with another party, there is a willingness to adopt new products. Several interviewees felt that contract structures and procurement routes were largely responsible for creating an endemic 'build and defend' attitude. Consequently, if a material or practice is shown to work then there is little desire to explore alternatives. In this way existing practice becomes entrenched under the mantra of "*it's the way we've always done things*". This leads to the common industry view that imperceptibly slow change is typical and radical change almost unimaginable.

"It's all about risk. Everything we do, all our contracts are set up to offload risk and minimize damage to any one party. It's a very litigious sector. Until that changes it's going to be very difficult. For instance, being able to roll out a circular economy approach to a building- which we very much want to do - we've done it in the business but not in the UK. The kind of contracts we have, and the idea of risk, and 'who's fault was this?' and stuff like that needs to change from where we are at the moment because it just won't work."

Sustainability Manager – Multinational contractor

This is compounded by the industry's reluctance to discuss failures. Owing to an understandable fear of damaging their reputation, few firms speak openly about their failures, and many outwardly present only success stories. Consequently, the valuable learning generated from failures is not transferred between firms. This results in the same basic mistakes being made time and again by different practitioners. Anecdotal stories of such failures pass around the industry, which in turn reinforces a general scepticism of alternative materials. By this means myths and misinformation are disseminated in the absence of guidance that could prevent failures.

Interviewees felt that many of these entrenched attitudes could be overcome by earlier engagement of specialists further down the supply chain. For example, encouraging design teams and contractors to work with technical experts from material producers can help allay concerns about performance and highlight required changes in the construction programme. Changes in contract structures and a move away from the typical competitive tender route based solely on price could also contribute to changing this culture. However, concerns of this nature are long-standing, with numerous reports offering similar criticism over a period of decades.

"The attitude is 'build and defend'. It's defend your position. People get defensive very easily because 9 times out of 10 if something happens and there's a mistake, there's a cost to it and then it's on somebody's doorstep. The client won't want to pay for it so they'll go for the contractor first, and the contractor will go for us and it's just a merry-go-round. We'll go to the supplier, the supplier will go to the sub-contractor and it's just such an unproductive approach. I think it purely comes about through the procurement of the building contracts and how that interaction works."

Architectural Technologist – Specialist architectural practice

5.5.1.4 Costs

"In the work that we've done…we've found a very direct link between managing embodied carbon and reducing costs. You do one, you'll get the other."

Chair of Embodied Carbon Task Force

Survey results suggested a perception of high costs was restricting the uptake of low carbon materials. Yet all interviewees, except one, believed that reducing embodied carbon should not increase costs. Interviewees highlighted a common perception that low carbon options may incur a 'green premium' or additional consultancy costs that may not deliver value. However, they believed that this green premium had diminished over recent years and that relatively low consultancy costs are usually justified by material savings. In many cases the additional cost is not incurred directly in the material purchase but in consequent changes to the construction programme; often a result of late material substitution or changes in design. Furthermore, many alternative materials are not seen to offer savings on an elemental basis but can be demonstrated to yield savings in the total project cost. The earlier alternatives are included in designs, the easier it is to avoid costly changes to the construction programme and overcome the limitations of elemental costing.

"I think there are a lot of opportunities missed by not thinking about things holistically all the way through the process. There's diminishing returns the later you start considering these things, the less reduction you're going to achieve and probably the more it is going to cost. I think that's one of the biggest barriers, people think it'll cost more. You know, sometimes it might but often it won't if you just took the time to think about it."

Senior Engineer – Large multidisciplinary consultancy

Interviewees also stated that effective life cycle costing was critical to increasing uptake of alternative materials. Despite significant industry lip service to the contrary, most interviewees felt that life cycle costing was not being implemented and, consequently, materials that require less frequent replacement or offered potentially greater end of life value were being overlooked. Opportunities to implement such options are further restricted by the tendency of clients that are not the end users to prioritise options with the lowest up-front cost.

"Cost with embodied carbon for me is the biggest issue. There's a lot of cost neutral stuff you can do to reduce some of the high impact areas but I think the real business case only gets made if you look over the life of the building. I think that doesn't happen enough. We're not life cycle costing…it's not happening even though it is supposed to happen."

Sustainability Manager – Multinational contractor

In essence, whilst in some instances low carbon materials may cost more, in many cases increased costs are really a symptom of other barriers. Encouraging early consideration of design options and building a business case around life cycle costing can mitigate concerns about cost. It is clear that cost and quality will continue to reign as the principal client priorities. Therefore, if embodied carbon assessment and reduction is to become commonplace, practitioners will need to clearly demonstrate the value of alternative materials in these terms.

"A lot of more sustainable options are not a quick substitute, there's other draw backs potentially from using them. If you've designed with that in mind then that's fine but if you design with something else in mind, even though the material itself might not cost a lot, the impact it would have on the design might cost more. Most things do come down to cost but I don't think it is necessarily the outright cost of the material itself."

Senior Engineer – Large multidisciplinary consultancy

Many interviewees also expressed a belief that costs would continue to fall as embodied carbon becomes a more mainstream concern. Many of the industries supplying low carbon materials have the potential to exploit significant economies of scale if demand increases.

5.5.1.5 Low value of materials

Materials still retain a low value relative to total project costs, limiting consideration of material reduction strategies. Current valuation schemes also fail to assign any significant end of life value to materials. There is a widespread perception that once materials are on a building they are simply "*waste in waiting*". Interventions are required to change the perception of buildings approaching end of life from being liabilities (associated with high demolition costs) towards being valuable "*material banks*". However, interviewees felt a substantial market for recycled or reused materials would not emerge without Government intervention. The EC (2014) set out their intention to investigate this issue in a recent communication, however, this work remains at an early stage. Interviewees also felt that manufacturers needed to bear a greater degree of responsibility and that building rating schemes could better address this issue.

*"We need to have a greater value **somehow** of materials once they are no longer wanted in a building …People don't think they are resources as soon as they're on a building. Once they're on a building it's basically waste in waiting. It's really bizarre."*

Senior Engineer – Large multidisciplinary consultancy

5.5.1.6 Knowledge, understanding and skills

Current industry understanding of embodied carbon varies widely across professions, firms and between individuals within those firms. Interviewees expressed a common opinion that the importance of embodied carbon and material selection is still regularly underestimated. One interviewee described it as "*terrifying how little people knew in the industry about it*". Whilst over recent years understanding of the basic terminology has improved, only a small minority of professionals in the industry are engaged in regular embodied carbon assessment. Some of these practitioners have been working in this area for over a decade and have developed significant skill sets. The core challenge is in spreading their knowledge throughout a highly fragmented industry.

"I think the industry knows what it is, generally speaking. If you ask the average architect or engineer, 'do you know what embodied carbon is?', they'll say 'yes'. When you then say, 'OK, do you get involved with measuring it?', and you might get 5%, probably not even that, 1 or 2% are actually involved in measuring it. In terms of technical know-how there is still a great dearth of knowledge out there. It's a select few at the moment."

Chair of Embodied Carbon Task Force

Interviewees stressed the need for improving information exchange between professions, as it is only if all project participants are engaged and understand the theory as well as the practice that progress will be made. A number of interviewees stressed the need for greater support by professional institutions (e.g. UKGBC, RIBA, IStructE) in encouraging this communication, knowledge and data sharing. The maintenance of common repositories for information sharing, such as the UKGBC's Pinpoint platform (UKGBC, 2014b), are key in reaching the broadest audience.

Many companies are still hampered by an inability to effectively roll over learning from project to project. This is particularly the case for smaller companies that cannot afford specialist staff to develop in house expertise. Larger companies are often guilty of restricting expertise to specific individuals – 'materials' or 'sustainability' specialists – that fail to disseminate this knowledge amongst general staff, meaning this knowledge is lost when those individuals switch firms. In companies of all sizes, establishing routine processes that allow building through incremental learning will be critical in supporting this knowledge development.

"I know our company quite well and even within our company there is a huge range from people who understand all the complexity of the detail to people who still are not even sure what carbon footprinting is, let alone why you should do it or how to do it…the general awareness and knowledge is definitely increasing but it's not particularly high yet"

Senior Engineer – Large multidisciplinary consultancy

There also remains a significant challenge in spreading knowledge and demand for low embodied carbon structures from large to small clients. Interviewees stated that a spread from the largest developers down to the next tier of clients – generally large companies producing buildings for their own use – is already occurring. However, interviewees feared that the perception of increased consultancy costs would prevent concern spreading to smaller clients.

The introduction of simple assessment tools could be invaluable in supporting assessment amongst smaller construction firms. This could be supported by flexible legislation that encourages recognition of embodied carbon without requiring full assessment. For example, the introduction of a series of approved solutions for embodied carbon as an Allowable Solution would encourage architects at small firms to specify a solution with lower embodied carbon without the need for a full, complex assessment. Sustainability consultants also have a crucial supporting role to play in the coming years until larger practices bring these skills in house.

Several interviewees also emphasised the need for universities to include a greater focus on embodied carbon in undergraduate courses. A new generation of designers from certain institutions have had these issues "*drilled into them at university*" but the majority of the industry's work force, including those who must lead on this issue in the coming decade, are already in practice. Therefore quality training for practicing designers is also essential. Greater training for tradesmen and installers will also be necessary to ensure familiarity with a broader range of materials and products and adherence to the often higher quality of installation and finish that is required.

5.5.1.7 Demonstration projects and product testing

Most interviewees identified a need for more shared case studies to prevent designers from re-inventing the wheel each time. For many, proving real world performance is the only way to overcome industry scepticism and demonstration projects are seen as the best way to do this. Underperformance of construction products is commonplace in the industry, as evidenced by widely documented performance gap problems (Zero Carbon Hub, 2014). This has resulted in a lack of faith in figures from manufacturers and models. This can only be overcome through greater in situ testing and post occupancy evaluation. Unfortunately, many within the industry are reluctant to confront real world performance and potential failures because of the associated liability and reputational risk. One interviewee cited example performance studies of public buildings that have been suppressed either because they failed miserably or because they performed exceptionally and participants were reluctant to share their secret.

5.5.1.8 Early engagement

A lack of early engagement was consistently noted by interviewees as a significant barrier. Opportunities to adopt more sustainable solutions were regularly overlooked because they were only considered late in the project. Contractors and sustainability specialists were often not consulted until after critical design decisions had been taken; and the flow of information between specialists and the design team was often not on a sufficient cycle to allow the greatest impact.

"I find that, because I'm typically outside of a design team, I'll often get brought in in a bid stage, [with them] saying 'oh what can we do that's really interesting' and I help them make a bid and then maybe never hear from them again. If you do it might be like 'how can we make this sustainable'? 'What do you mean, you can't make it sustainable? It is or it isn't'. There's this awful project example where the project was on site and the client had brought in a sustainability consultant who was saying all the right things but you can't design for deconstruction if you're already building something. It was nonsensical at that point in time."

Senior Engineer – Large multidisciplinary consultancy

Early engagement of the full supply chain, including sub-contractors and suppliers, is critical in leveraging the broadest combined knowledge and specialist insight, which will lead to better design decisions and prevent the need for expensive re-design or re-work. This requires allocating sufficient time at the early design stages to allow for such engagement and consideration of material options. This supports the findings of the Arup study that on more sustainable projects material choice is generally considered earlier in the design process and for longer (Arup & WBCSD, 2012).

"Early engagement is a thing we need to do…as with all sustainability issues, we're always saying they need to be considered earlier because they're not. As

a contractor…we tend to get involved slightly later and we see instances all the time where issues are being brought up, either we're bringing them up or they've been left to this stage, but basically too late. Design decisions have already happened or contracts have already been put in place. To go back would mean a load more money, re-work, re-drawing…We need early engagement with all stakeholders but the supply chain really…because that's where the solutions come. Either contractor, sub-contractor or supplier or ideally all three."

Sustainability Manager – Multinational contractor

5.5.1.9 Negative perceptions of low carbon materials

Scepticism towards many alternative materials clearly remains amongst some parts of the industry. Advocates for low carbon construction are often not taken seriously, with many interviewees offering anecdotes about colleagues responding with an attitude of "*here's the green person banging on about something green*". There remains a significant challenge in changing these entrenched attitudes.

The core challenge lies in taking embodied carbon into the mainstream, positioning it as compatible with existing goals and prominent campaigns (such as resource efficiency and circular economy principles) and associating it with a broader array of materials. One interviewee drew a pertinent parallel with operational energy, which over the preceding 20 years has gone from a "*niche, hippy thing to do*" to a routine consideration.

5.5.2 Drivers and opportunities

5.5.2.1 Moral convictions

In the absence of significant regulatory or client drivers, the moral convictions of individuals have driven progress on embodied carbon thus far. Interviewees felt that many individuals within the industry were deeply passionate about the built environment and exhibited a strong desire to minimise environmental impacts. However, pragmatic considerations about cost, quality and buildability will regularly trump personal convictions about sustainability. Consequently, there remain limited instances where moral reasons drive material decisions. In these instances the individual is usually supported by a like-minded client.

There are limited historical precedents for moral convictions driving change in the construction industry. In cases where this has been successful, such as the greatly improved attitudes towards on-site health and safety, these good intentions have been supported by strong regulation. Thus, whilst in the short term there remains some scope for further change to be driven by the moral convictions of clients and practitioners; in the long term additional regulatory or financial drivers will be needed as few within the industry are in a position to act on personal convictions.

"I think we need to make sure that the regulations make it happen. Without that it'll be left to the moral leaders to continue their work but it won't become an industry."

Chair of Embodied Carbon Task Force

5.5.2.2 Establishment of an embodied carbon community

Leading industry practitioners are increasingly sharing best practice and a nascent embodied carbon community is forming. There are a growing number of industry events on the topic with increasing attendances and interviewees expect this community to continue expanding. This will drive interest and action on embodied carbon and improve the dissemination of information and best practice.

"I feel the community has come a long way in the past 12 months and we sit in rooms and have coffee together and talk about how we do things and how we could do things better or more consistently as an embodied carbon community. I think that's quite important."

Senior Engineer – Large multidisciplinary consultancy

5.5.2.3 Client requirements

Major clients are increasingly incorporating environmental and social considerations into their project evaluation processes. As discussed in Chapter 2, a growing number have shown an interest in embodied carbon with several making clear assessment or reduction commitments. A group of large developers are regularly communicating on this and other issues. This will help spread best practice, ensure client demands are robust and lead to further interest from smaller clients. Anecdotal evidence of this spread was reported by the interviewees. However, many feared perceived cost increases could prevent demand from spreading to the smallest clients.

Much of the current client interest is driven either by increasing CSR commitments or by the moral convictions of individuals within those firms. There may be an opportunity to engage further clients in consideration of embodied carbon by targeting key individuals, such as directors, in those firms. However, in the long term, only ensuring buy in from select individuals will not be sufficient, as development teams must be convinced of the value in addressing embodied carbon, otherwise requirements may be introduced but not enforced.

Interviewees stated that greater guidance for clients would be welcome. In the absence of clear and simple guidance, such as a detailed client procurement guide, some clients may over analyse options and suffer from a paralysis of choice. Clear targeted reductions, such as British Land's commitment to targeting 5 key materials (British Land, 2014), or M&S's focus on 'carbon hotspots' (Marks and

Spencer, 2014) can help in this regard. Ultimately, clients are in a strong position to drive embodied carbon assessment and do not require enabling legislation. Consequently, increasing client demands are likely to be the greatest driver of embodied carbon assessment in the near term.

"We talk very much about our social, economic and financial contribution as a whole. Every decision you make you have to look at the financial bottom line but what's the environmental bottom line as well? What's the social bottom line?... You can justify maybe coming below the hurdle for financial return… if you can say environmentally or socially we're doing this, this and this…We have people in the business now starting to think like that. They're thinking not just about the financial bottom line, they're thinking of everything else as well."

Assistant Head of Sustainability – Large client

5.5.2.4 Business opportunities

There is a growing business case for tackling embodied carbon that is principally motivated by four factors: perceived cost savings associated with a reduction in material use; establishment of a reputation for good environmental management; increased resilience to resource scarcity and price rises; and the opportunity to be 'ahead of the curve' with regards to future legislation (WRAP, 2014b). Generally speaking, embodied carbon assessment is seen as a means of promoting resource efficiency, which many interviewees felt could yield significant long term savings. Numerous companies have already demonstrated associated costs savings. However, most interviewees felt this business case had yet to be effectively disseminated throughout the industry.

Some interviewees perceived opportunities for UK companies to be world leaders in a growing industry of embodied carbon assessors. As global interest grows there are opportunities to export services calculating embodied carbon, advising on reduction strategies, or training local practitioners on these techniques. Examples already exist of UK based companies advising on overseas projects. One interviewee felt that if this opportunity was not swiftly seized – by developing skills and nurturing the UK market – it was likely that other nations would overtake the UK and provide these services.

"The activity of measuring carbon and advising on how to reduce it in buildings is obviously a part of the green economy. It keeps people in work and it's an expertise that we may have an advantage here in the UK on, which can be sold abroad. It's good for international competition and income, exporting that kind of expertise. In that sense I think it is obviously a good thing."

Sustainability and LCA Expert – Research technology organisation

Several interviewees felt that the drive to reduce embodied carbon and material usage may require greater use of unconventional ownership models (such as product leasing) and performance-based specification. Some interviewees felt that the focus of product manufacturers must shift from increasing the volume of sales to providing the same service level with reduced material usage. For material producers this presents an opportunity to retain current profits whilst reducing embodied impacts. However, it may require substantial changes in business models and marketing approaches.

5.5.2.5 Regulation

Survey results suggested that 'regulation limiting embodied carbon in construction' could potentially be the greatest driver of alternative materials use. Regulation has long been a critical driver of change in the construction industry and interviewees felt it would be essential in addressing embodied carbon. Whilst moral convictions, the demands of particular clients and perceived business opportunities may drive some uptake of low carbon materials, interviewees felt that a significant proportion of the industry would only respond to legislated requirements.

"At the end of the day, the drivers will always be statutory requirements put upon them to do these things, a huge proportion of the marketplace will only respond to that."

Sustainability and LCA Expert – Research technology organisation

Interviewees suggested a variety of means of implementing regulation, including: forming a new Part of the Building Regulations governing embodied carbon; including embodied carbon in a revitalised Zero Carbon definition; introducing measures addressing embodied carbon as Allowable Solutions; and simply mandating measurement of embodied carbon as part of the planning process. The best means remained a source of much debate, with interviewees stressing the need for a holistic approach that balanced embodied and operational emissions. Some interviewees believed better product and building level data would be required before regulation would be feasible or effective. Others argued that the simple act of mandating measurement would generate such data in short order.

Many interviewees believed the current government lacked the political appetite for introducing additional regulation, fearing it may be perceived as another costly layer of "*unnecessary bureaucracy*" on an already "*over-burdened*" industry. However, several interviewees believed such regulation would be received enthusiastically by many in the industry as it would provide them with justification for dedicating time to an issue they perceive to be important. A key factor in how such regulation would be received is whether or not it is seen to contribute in a positive and flexible way to the design process. When drafting such regulation the emphasis should be on encouraging a variety of good practices not generating additional compliance calculations. Many interviewees felt that the introduction of such regulation could support improved building design; drive significant innovation in product supply chains and rejuvenate the market for recycled and reused materials.

"Architects and engineers want to produce better buildings. If by managing embodied carbon, as well as operational carbon, you're producing a better building then there'll be no resistance at all. But you've got to think about the drivers for that. The drivers need to be cost and regulatory. If you've got the drivers there it'll just get done. No-one will even begin to question it."

Chair of Embodied Carbon Task Force

5.5.2.6 Building rating schemes

The inclusion of incentives for embodied carbon assessment in BREEAM and LEED was cited by some interviewees as a potential driver. However, it was felt that this may only motivate certain clients and affect a limited range of structure types. One interviewee also expressed a concern that the current approach which incentivises only full scale assessment may have alienated smaller firms and overlooked opportunities to encourage other less onerous actions.

5.5.2.7 BIM and automation

Several interviewees also identified opportunities to automate carbon assessment through attaching carbon figures to material quantities in BIM. This would allow designers to easily enumerate the carbon impacts of their design decisions. This could support simultaneous component and project level comparisons and allow for assessment of different options that meet an overall carbon target. However, some interviewees expressed general concerns that BIM uptake may not meet expectations and potential benefits may be overstated.

"If it is automated and integrated with BIM, then you can imagine a scenario where they [designers] are making step-by-step decisions and observing the results as they are going along - maybe against a high level target. Increasingly putting more and more detail into the model and making sure that they still stay within the targets. Just like with cost of the building. You have a budget, you set some high level budgets to the different elements in the building and you work within those. They may get juggled around a bit but ultimately the budget has to be fixed. That's got to be the way this works, just with a carbon footprint target instead of money."

Sustainability and LCA Expert – Research technology organisation

5.5.3 Other considerations

5.5.3.1 Benchmarks

Interviewees repeatedly expressed concern about the lack of robust benchmark data on embodied carbon. At a building level, designers are currently restricted to the RICS benchmarks (RICS, 2012), WRAP resource efficiency benchmarks (WRAP, 2014a), entries in the WRAP embodied carbon database (WRAP & UKGBC, 2014) or results from past projects. These sources cover a limited range of building types and are based upon small samples. Component level benchmarks are not yet available. Even within these data sets there is limited scope for accurate benchmarking owing to the variety of data sources used and the impact of project specific factors on total results. For example, foundations can constitute a significant share of the total embodied carbon but depend heavily on site ground conditions. For similar reasons, there is limited scope for benchmarking against notional reference buildings. The gathering of more robust benchmark data will undoubtedly require a massive data collection effort over a period of years. Several interviewees felt the simplest way to accelerate this process would be to mandate measurement through regulation. Some interviewees also felt that the development of a robust database of building level benchmarks must be supported by the simultaneous development of a common LCI database for materials. Such a common dataset would allow fair comparison between designs. Benchmarking at a product level could also encourage competition between material producers and drive decarbonisation of manufacturing processes.

"I think the starting point will be to work on a benchmark per sector. For example, there's a 12 storey office block with air conditioning would be roughly x. Then people can start looking at how they can reduce that in the same way as we look at how we'd reduce cost."

Director of Sustainability – Professional institution

Currently there is no means by which to bridge the gap between sector level and project level targets. Ensuring future building level benchmarks and targets are consistent with national carbon reduction targets will be key to achieving the required level of emissions reduction. One interviewee stressed that creating such a link was "*essential*" if progress towards the targets was to be managed effectively. This topic is further addressed in Chapter 6.

5.5.3.2 Role for institutions

Professional institutes play a critical role in the construction industry. Interviewees felt that, thus far, there had been minimal engagement on embodied carbon from the institutes, with some notable exceptions such as the RICS methodology (RICS, 2012). There is a great opportunity for professional institutes to provide legitimacy and impartiality to data sharing schemes (such as Carbon Buzz (RIBA & CIBSE, n.d.) and the WRAP embodied carbon database (WRAP & UKGBC, 2014)); facilitate knowledge transfer between firms; and support the development of an embodied carbon community. Institutions can also help address the current shortage of skills through training courses and guidance and provide funding for demonstration projects and testing of novel materials. Further targeted support for small firms, such as the provision of basic calculation tools and benchmarks, would also be welcomed. There may also be opportunities for institutions to motivate action through implementing voluntary standards or targets for embodied carbon. However, it is important to remember that voluntary standards, whilst desirable, are not necessarily effective in embedding change. Whilst the suggested actions varied, interviewees' unanimous desire was that institutions take a more active role in the embodied carbon debate.

5.6 Discussion and recommendations

The principal objective of the research presented in this chapter was to understand the economic, technical, practical and cultural barriers preventing construction professionals from selecting a variety of materials commonly identified as being lower in embodied carbon. A review of previous studies assessing barriers to adoption of more sustainable practices in the construction industry revealed a common set of cultural and institutional barriers. The survey and interview results strongly suggest that these barriers also prevent alternative material choice as a means of mitigating embodied carbon emissions. Many of the observed barriers are common across materials with uptake restricted by: perceptions of high costs; a shortage of knowledge and skills; inadequate design time to allow consideration of novel options; inadequate information from material producers and an inability to establish an effective or collective chain of responsibility. Design teams are also hampered by the poor availability of product and building level carbon data and benchmarks.

The industry can seek to overcome these barriers by encouraging earlier engagement of supply chains, effective use of whole life costing, and changes to contract and tender documents. The industry must work harder to maximise the value sustainability consultants and material experts can bring to projects by ensuring initial engagement in the early project stages, regular communication and appropriate time for review of designs. Additional training is required for many practitioners, and firms engaging in their first embodied carbon assessments must have structures in place to ensure learning is rolled over from project to project and disseminated internally. The industry must also share the accumulated knowledge on embodied carbon. This includes uploading data to common repositories to allow for benchmarking; sharing standardised reporting forms and openly discussing their successes and failures. Similarly, low carbon product manufacturers must improve the synthesis and dissemination of information to designers. Improvements in this regard are critical in bridging the gap between knowledge and perceptions of low carbon materials.

The industry must not wait on regulation to act but continue to develop the business case and be proactive in encouraging clients to engage in assessment. It is important that designers and contractors do not simply view themselves as 'project executers' (Wong et al., 2013) but as key 'middle-actors' (as described by Janda, Killip, & Fawcett (2014)) that can promote best practice downstream to clients and upstream to policy makers. In many cases, practitioners are still struggling to demonstrate the value of carbon assessment to clients. Without a more robust business case, supported by evidence of the anticipated benefits – particularly for the disputed cost savings – it will remain difficult to engage clients.

Projects that have successfully measured and reduced embodied carbon typically benefit from a highly motivated client that places clear and challenging requirements in the tender documents, common incentives in contracts, and encourages early engagement of the full supply chain. These client-led actions are the simplest way to overcome partisan relationships between professions and to ensure collective responsibility for carbon reduction. There is a clear opportunity for clients to motivate further action on embodied carbon without enabling legislation. Clients must also be proactive in sharing their expertise and experiences, allowing for mutually beneficial improvements such as standardising embodied carbon reporting forms for sub-contractors. Engaged individuals within client organisations should seek to include embodied carbon assessment within their mandatory or voluntary carbon disclosure to embed consideration and continuous improvement within their organisation.

There is a role for professional institutions to facilitate this knowledge transfer between firms and foster an embodied carbon community. Cultivating a healthy community of experts and advocates will be vital in ensuring embodied carbon remains an ongoing concern within an industry that faces many competing agendas. Institutions can provide training courses and guidance; fund key demonstration projects; independently gather cost data to flesh out the business case; and help disseminate lessons learnt by early actors. The active engagement of professional institutions could also bring credibility to an issue that is still viewed with scepticism by some policy makers and industry practitioners.

Universities can support knowledge and skills development by including a greater focus on embodied carbon assessment and low carbon design in their curricula. There is also scope for further qualitative research charting the awareness and uptake of alternative materials, monitoring the emergence and dissolution of barriers to their use, and providing advice for practitioners and policy makers on practical steps to overcome these barriers.

Ultimately regulation will also be required to build upon the early work of moral leaders. This regulation must simultaneously motivate embodied carbon assessment and support producers of low carbon materials. Local and international precedents have already been discussed at length in Section 2.3, and the options for future regulation are considered further in Chapter 7. The combination of early industry action and regulation could support swift development of expertise, faster data gathering and the growth of an industry with significant export potential. There is an opportunity for early actors to become world leaders in a growing industry that will support skilled jobs, develop the market for alternative materials and achieve significant reductions in GHG emissions. Promoting the UK's comparative advantage in low carbon manufacturing by stimulating domestic demand for low carbon building products could support the strategic goal, set out in Construction 2025, of making the UK a world leader in low carbon exports. However, this is unlikely to occur without substantive new drivers.

In the parlance of innovation theorists, embodied carbon assessment and the manufacture of low carbon products remains within the 'formative phase'. Innovation theory suggests that growth beyond this phase typically necessitates institutional changes, entry of new firms and formation of advocacy groups. Unfortunately there is little evidence, as yet, of significant institutional changes, with minimal engagement from professional institutes and the exclusion of embodied carbon from the mainstream political discourse. New firms developing low carbon building products have struggled to gain a foothold in a market dominated by a handful of large producers. The UK has also seen significantly higher failure rates for new producers compared with countries such as Germany and France (Newman, 2013). Furthermore – with the notable exception of the timber lobby – advocacy groups for low carbon products, such as the Alliance for Sustainable Building Products, are still in their infancy and are small relative to their mainstream counterparts. It is unlikely that such small groups representing a diverse range of products will ever develop the lobbying capacity and political influence of the dominant producers. In the meantime, uptake of low carbon building products has often been restricted to niche-like environments created by unique project contexts (Jones et al., 2015).

Geels (2004) outlines how technologies developed in niches can emerge through 'windows of opportunity' to change an overarching socio-technical regime and break existing industry path dependencies. In the case of embodied carbon assessment and low carbon building products it remains to be seen how such a window of opportunity could materialize. Whilst climate change has applied pressure at a landscape level and resulted in sectoral targets for emissions abatement, accounting and regulatory approaches have prevented translation of this pressure into action on embodied carbon. It is likely that such a window of opportunity will only be generated in one of three circumstances.

First, if the marginal cost of abating embodied emissions was significantly less than abating operational emissions. Conceivably, as designers are forced to approach the nearly zero energy buildings envisioned by the EU EPBD, this may necessitate the adoption of increasingly complex and expensive technological solutions to achieve marginal increases in operational energy performance. In such circumstances it may be more cost effective to achieve comparable whole life emission reductions by adopting alternative building materials with reduced operational energy performance but lower embodied carbon. However, if whole life cycle savings were to be effectively valued - allowing for selection of the cheapest abatement option - it would require recognition of both operational and embodied emissions within standardised accounting procedures and regulation. Such amendments may help achieve the *"cost-optimal"* balance targetted by the EPBD but would require resolution of the previously discussed concerns surrounding allocation of embodied emissions and generation of product data.

A second window of opportunity could be stimulated by the combined uptake of BIM and life cycle costing. Attaching carbon and cost information to components in BIM could ease the calculation process and allow designers to explore the embodied emissions implications of alternative designs. The additional retention of building material information also has the potential to support greater recovery of materials and value at end of life. Both of these factors could highlight the significance of materials in carbon and financial budgets. This could alter the mind-set of designers and make it easier to generate a business case around material changes. However, the limited uptake to date of life cycle tools such as Rapiere suggests that additional incentives beyond current rating scheme innovation credits may be required to stimulate uptake. The UK industry has also experienced substantial difficulties in rolling out BIM Level 2. Implementation of higher BIM Levels will doubtless prove even more challenging. Retention of building material information also requires retention and updating of the corresponding building models over many decades. It remains to be seen if this will be achieved in practice, particularly through transfers of building ownership.

A third window of opportunity may arise during the 5th-8th Carbon Budgets as the UK operates within an increasingly constrained carbon space. If the UK has exhausted more cost effective mitigation options elsewhere, or is struggling to achieve the changes in behaviour and infrastructure necessary to support targeted emissions reductions in other major sectors of the economy, past actions suggest that the remaining burden is likely to be placed upon more heavily regulated sectors, such as construction. Similarly, beyond 2050, the net zero emissions goal implied by the Paris Agreement may require that any remaining emissions can be cost effectively offset with additional carbon sinks. Given the UK's current land use and prospects for CCS, there is clearly a limited volume of low cost carbon sinks that the UK can develop. Achieving further reductions through additional mitigation measures for embodied carbon in construction may prove preferable to further changes in land use or dependence upon expensive negative emissions technologies such as bioenergy with carbon capture and storage. This could result in a progressive ratcheting up of construction emissions reduction targets which would necessitate more substantive action on embodied carbon. The likelihood of such a scenario is further explored in Chapter 6.

5.7 Study limitations

The study was limited by a number of factors discussed in the following paragraphs. The survey's relatively small (47 respondents) convenience based sample, whilst not intended to be representative, fell below the desired sample size; and a particularly poor response rate was observed from certain professions (e.g. quantity surveyors). This may be explained by a combination of the survey length and the more general phenomenon of declining response rates attributable to survey fatigue. The online platform, means of distribution and survey title may also have biased the survey towards respondents from particular demographics and with specific positive or negative experiences that they wished to share.

The qualitative approach of the study, whilst providing useful insight into many questions, provides incomplete or conflicting answers to some questions and depends upon unbiased reporting of experiences by practitioners. Whilst many of the presented results support those accumulated from other studies of 'sustainable' or 'green' building, it remains difficult to determine if these results reflect established 'myths' within the industry or real, commonplace, experiences. By offsetting survey questions in both general terms and across an array of specific materials an attempt was made to distinguish the differences between perceptions and experiences. Triangulation with interview results also helped to provide a more nuanced interpretation of survey results. However, there remain many unresolved questions. Definitive answers to some questions, such as whether or not low carbon materials increase project costs, can only ultimately be resolved through the collection of real world cost data. This research gap could be addressed through case studies or a data collection project by an established industry body, such as the RICS. For instance, the confidential data accrued by the Building Cost Information Service (BCIS) could be sufficient to determine typical cost discrepancies between comparable designs using different materials. In the absence of such data, studying perceptions and the root of cost increases can still provide insight, as it is often perceptions rather than reality that influences uptake.

Other research gaps include understanding how concerns around embodied carbon spread within client organisations, and exploring the implications for material manufacturers of a low embodied carbon future. Reduced use of conventional materials, and the greater uptake of alternative materials, has the potential to interfere with the existing dynamics of the sector, reducing the market share of currently dominant producers. This in turn has the potential to inflict substantial structural changes on the economy. It is apparent that more work needs to be done to develop a thorough understanding of these potential impacts. Much additional data gathering is needed to develop robust project level benchmarks and a methodology is needed to link these with sector emission reduction targets. Further research is also required to resolve the debate around the most appropriate means of regulating embodied carbon and detailed proposals require development. These issues will be returned to in later chapters.

5.8 Summary

A multitude of barriers to greater uptake of low carbon building materials were identified through a literature review, industry survey and practitioner interviews. These include: negative perceptions held by clients and colleagues; expectations of additional cost; a shortage of knowledge, skills and information; litigious industry culture; and practices that prevent early engagement and effective allocation of responsibility to project participants. Whilst prior academic research has principally focussed upon overcoming technical barriers to material adoption, in many instances these broader cultural and economic barriers are more significant. If embodied carbon assessment is to become a mainstream concern, provoking a corresponding increase in the use of low carbon building products, then these barriers must be overcome. This will require additional practitioner training; data gathering; contract and tender document changes; and development of a more robust business case. These activities must be supported by greater engagement from the professional institutes.

In the short term, clients have a critical role to play in driving progress and spreading best practice. In the medium term, additional regulatory drivers will be necessary. The scale of reductions required in the long term is uncertain and may be subject to change. There are a range of conceivable circumstances in which suitable 'windows of opportunity' could develop, allowing low carbon materials to emerge from their existing niche. However, such circumstances are unlikely to arise in short order without additional interventions from policy makers or resolution of outstanding industry debates.

Though this chapter has presented a comprehensive overview from the perspective of practitioners involved in the design and construction process, additional studies must address the views of clients, material producers and end users. Additional work is also needed to link sector carbon reduction targets with project carbon intensity targets, and to describe the range of measures that may be required under different future scenarios. Ultimately, an understanding must be developed of how the costs and social impacts of embodied carbon mitigation compare with alternative mitigation options. These issues are explored in the following chapters.

6. Integrating sector and project level embodied carbon data

Q: Given the diverse range of projects in the industry, do you think it will be possible to establish common benchmarks for embodied carbon?

A: I think it is possible…you can link an impact target for a building category to a functional unit. The problem is the allocation of the industry's total emissions and measuring the total emissions as a part of the overall economy. That's the challenge.

Excerpt from interview with Sustainability and LCA Expert reported in Chapter 5

6.1 Introduction

Previous chapters have highlighted the need for embodied carbon reduction in meeting strategic sector carbon reduction targets and discussed the merits of a range of design strategies and alternative materials. Irrespective of the particular materials or design strategies adopted, design teams require a project target for embodied carbon. Past experiences have shown that the most effective projects feature a clear target embedded in common contract documents to ensure collective responsibility and alignment of aims between project participants. To this end, the industry has expended significant resources in data gathering schemes such as the WRAP Embodied Carbon Database (WRAP & UKGBC, 2014). This data, alongside published benchmarks from groups such as the RICS (2012) and WRAP (2014a), are facilitating relative benchmarking between designs. However, this bottom up data has yet to be integrated with top down data representing overall sector output. This integration is crucial for design teams to assess not only performance relative to their contemporaries but absolute performance in the context of UK climate mitigation strategies. As Doran (2014) points out: "*currently embodied carbon assessment methods for buildings are based on comparing the life cycle assessment results of one building design with one or more other buildings – a relative comparison. This provides guidance on relative performance and allows for benchmarking. However, relative comparison offers no insight as to whether a particular building's embodied carbon emissions are consistent with global and, in turn, the UK's planned reductions in carbon emissions. As such, building designers have no way of knowing if their carbon mitigation decisions are reasonable, in the context of climate change*". This concern was reiterated by participants in the survey and interviews presented in Chapter 5. The absence of such a link leaves designers and educators unsure what range of emissions abatement options may be required in the long term and unable to focus upon development of appropriate skills and material expertise.

Similarly, from a policy maker's perspective ensuring future project targets and benchmarks are consistent with national targets will be key to achieving the required levels of emissions reduction. These targets may change with improved understanding of climate feedbacks; a likely ratcheting up of global emissions abatement efforts; and in response to levels of emissions reduction delivered in other sectors. If embodied carbon is solely assessed at the project level on a selection of sites, how can policy makers monitor national progress towards these targets? If regulation restricting embodied carbon is deemed a necessary response, how could an appropriate level be determined? These concerns can only be addressed by translating sector level targets into project targets and assessing impacts at both levels. Ultimately, establishing a link between the two will be essential if national policies are to be effectively operationalised. This chapter details the development of a novel UK Buildings and Infrastructure Embodied Carbon model (UK BIEC) that could provide such linkage.

The following sections describe the model, present results of a basic scenario analysis and discuss other intended applications. Specifically, Section 6.2 summarises the research objectives and introduces the basic model structure and system boundaries. Section 6.3 provides further detail on the model's underlying data sources, calibration and results of the scenario analysis. Section 6.4 discusses the implications of these results, alongside the broader implications of developing a construction sector with significantly reduced material use. Section 6.5 concludes the chapter with a brief summary.

6.2 Research methodology, objectives and boundaries

The principal objective of this chapter is to create an analytical framework that links sector level embodied carbon estimates and targets with project level estimates and targets. This framework takes the form of a novel empirical UK Buildings and Infrastructure Embodied Carbon Model (BIEC), which integrates output from a multi-regional input output model with a database of building life cycle carbon assessments. Scenario analysis is used to enumerate the influence of demand for new building stock and the role for design and material changes in meeting sector emission reduction targets.

The model is implemented as a Matlab script that draws upon two principal data sources. The first is a time series of aggregate construction sector embodied emissions from the UK MRIO model, previously discussed in Section 3.4. The second is a database of building level carbon assessments. The bulk of these assessments are extracted from the WRAP Embodied Carbon Database (WRAP & UKGBC, 2014), with the remainder sourced from a variety of academic and industry publications. The model database included 249 studies at the time the scenario analysis was completed. This figure has since increased and will continue to grow as embodied carbon assessment becomes commonplace within the industry.

The model considers the distribution of embodied carbon within 9 building classes and infrastructure across a common functional unit. The building classes were selected to correspond to available LCA and financial output data, see Section 6.3.1 and Appendix D for further explanation of the selection. Each class is represented by a carbon intensity function reflecting the range of embodied carbon per square metre of gross floor area ($kgCO_2e/m^2$ GFA) observed within that class in the database. Past and future projected output of each class is also represented in terms of the annual floor area constructed in m^2 GFA. The generation of these 'carbon intensity functions' and 'output profiles' is further discussed in Section 6.3. From these two elements an initial bottom up estimate of the total carbon footprint of each class is calculated. The sum of these class footprints is compared with the sector total from the MRIO time series. The difference between these totals is redistributed to the different classes in proportion to their calculated bottom up totals and a calibration loop adjusts the corresponding carbon intensity functions until the new totals match. This calibration process is further detailed in Section 6.3.5. The model has been calibrated over the period 2001-2012. This period was selected owing to the availability of both suitable building carbon assessment data and sufficient data for IO development. The model structure and data sources are detailed further in Section 6.3 and Appendix D.

The model development required a number of assumptions. The alternative assumptions considered and the criteria on which final assumptions were selected are detailed in a decision matrix in Appendix D. These decisions were subject to informal review by an independent academic. An initial version of the model was also presented at the 2015 Lolo Sustainability and Buildings Conference, with the underlying assumptions made open to review. Feedback from the conference attendees was incorporated into subsequent versions. Model version 1.0 presented in this chapter is intended to be the subject of further development. Desirable improvements are discussed in Section 6.3.9.

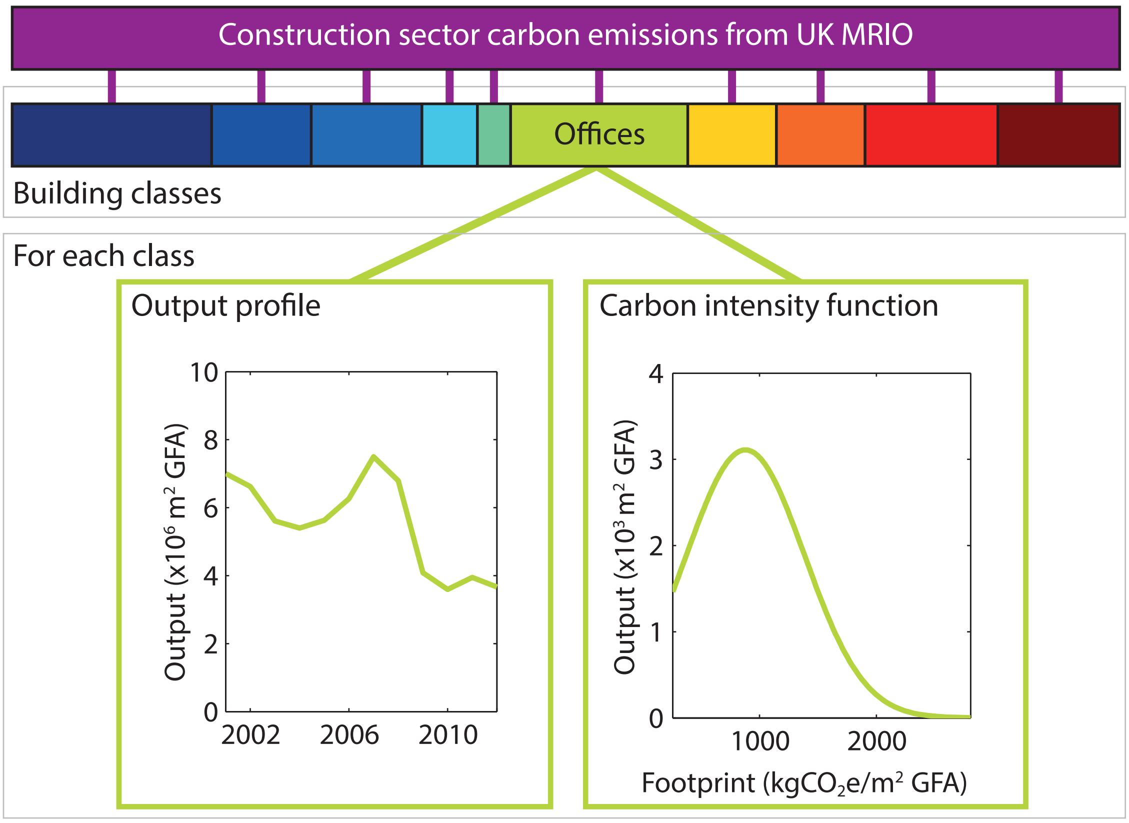
Scenario analysis is an analytic tool, commonly used within this field, for exploring the range of possible future outcomes. The analysis conducted here does not constitute a detailed economic forecast but merely explores potential futures based upon a range of reasoned assumptions. Using the UK BIEC model 27 scenarios reflecting different anticipated levels of economic growth, population growth and infrastructure investment are investigated in Section 6.3.6. These scenarios are used to anticipate the impact of future aggregate demand upon project carbon intensity targets. Given the absolute nature of national carbon budgets, in essence: the greater the growth in construction activity, the less carbon-intensive that activity must be. Thus, growth in overall activity has the potential to impose more severe carbon reduction targets at a project level, necessitating the adoption of different reduction strategies. These scenarios are implemented by extending the output profiles of each building class based upon data from a number of sources (see Section 6.3.6.1). The effects of anticipated grid decarbonisation are also incorporated based upon figures from DECC (2014).

The boundaries of the model are the embodied emissions incurred in the full international supply chains supporting new-build buildings and infrastructure within the UK. The model does not consider the embodied emissions implications of retrofitting the existing stock, see Sahagun & Moncaster (2012) for consideration of this crucial issue. The time period considered by the scenario analysis extends from 2001-2030. This period includes the completion of initial strategic targets set out in Construction 2025 and confirmed UK Carbon Budgets at the time of writing. Although the UK has targets extending to 2050, the share of these targets attributable to the construction sector has yet to be determined and the uncertainty associated with longer-term predictions of demand for building stock is much greater.

6.3 The UK Buildings and Infrastructure Embodied Carbon Model

The basic structure of the model is shown in Figure 23. The construction sector is divided into 10 classes, each of which is represented by a carbon intensity function and an output profile. The following sections describe the selection of the building classes and the means by which the output profiles and carbon intensity functions are computed.

Figure 23: UK BIEC model structure



6.3.1 Building classes

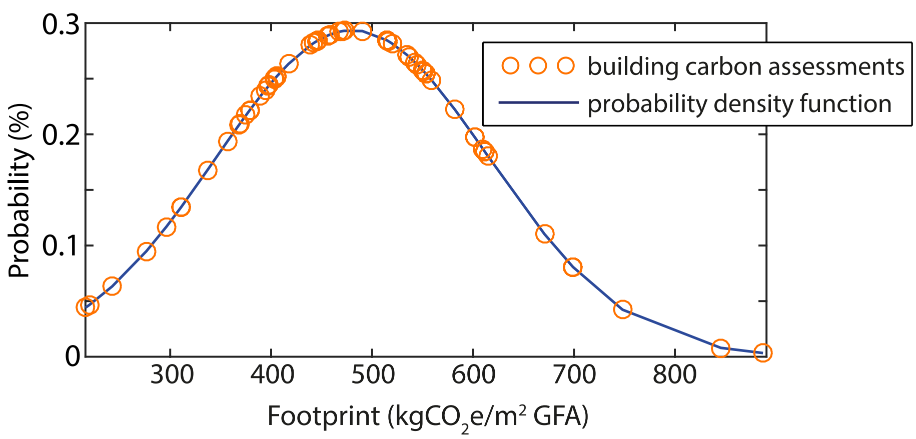
The 10 classes adopted (housing, factories, warehouses, education, health, offices, entertainment, retail, miscellaneous and infrastructure) broadly match those used within the ONS Output in the Construction Industry data series (ONS, 2015a). These classes are also broadly concordant with those from the principal carbon assessment data source, the WRAP Embodied Carbon Database (WRAP & UKGBC, 2014). As certain ONS classes, namely 'oil, steel and coal', 'garages' and 'agriculture', represent relatively small levels of diverse output without corresponding LCA studies, these classes are incorporated into the broader 'miscellaneous' class. The simplified class 'education' is equivalent to the ONS class 'Schools and universities'.

6.3.2 Carbon intensity functions

The carbon intensity functions draw upon an assembled database of building level carbon assessments categorised into the previously described classes. For each building class the model extracts maximum and minimum observed values from the database, sorts the data by carbon intensity per square metre, plots and fits a probability density function. See Figure 24 for an example for housing. The parameters of these functions (namely the mean, standard deviation and variance) are stored for further manipulation. A carbon intensity function of the same shape is then formed by distributing the annual output in each year according to the probability density function.

This approach implicitly assumes that the carbon assessments in the database constitute a representative sample of structures within each class, both in terms of the mix of annual output and the carbon intensity of construction. This is unlikely to be the case, as the sample is likely to contain a disproportionate number of exemplar and atypical projects. However, as further LCA studies are published and practitioners upload additional data to the WRAP database, the sample size will grow. As carbon assessment becomes routine it is likely that practitioners will upload more data on typical builds, changing the sample mix. This will reduce the influence of individual and atypical studies on the computed carbon intensity

Figure 24: Probability density function for housing



functions and improve the model's representation of reality. See Section 6.3.8 for further discussion of the model limitations.

For certain classes, i.e. entertainment and factories, few LCA studies are available. To prevent the inclusion of unrealistic carbon intensity functions based upon limited data, the model user can specify a desired minimum sample size as an input. In instances where an insufficient sample is found in the database, the model defaults to carbon intensity functions that form a normal distribution around the mean RICS embodied carbon benchmarks for that building class bounded by the upper and lower limits of the published range (RICS, 2012).

In the case of classes composed of a diverse range of structures, i.e. 'miscellaneous' and 'infrastructure', it is not possible to gather information on typical builds. Therefore, for these two classes, a separate approach was adopted using average carbon intensity figures per £ of output from the WRAP Resource Efficiency Benchmarks (WRAP, 2014a).

6.3.3 Output profiles

Currently no industry or public body gathers statistics on the floor area of any building class built each year. Consequently it is necessary to assemble such an estimate from a variety of data sources. The following section outlines the approach adopted.

Housing

DCLG publish regular statistics on house building in the UK covering starts, completions and tenure type (DCLG, 2015c). Floor area is not included in the statistics, however, this can be inferred by combining completions data with extensive studies into the size of new homes (RIBA, 2011). Estimates of new build housing floor area were thus computed for the period 2001-2013 by multiplying annual completions by average property size.

Non-domestic buildings

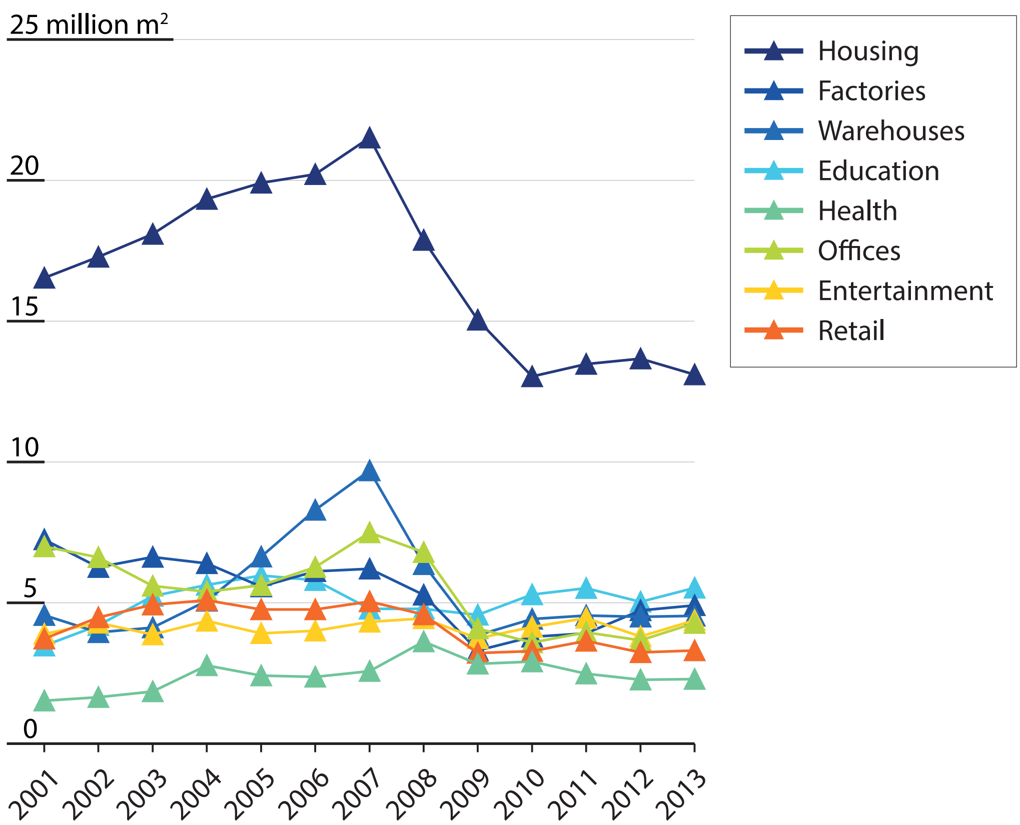
Non-domestic buildings pose a greater challenge as the Government's regular collection and publication of commercial and industrial floor area statistics ceased in 1985 (Clark, 2013b). The following paragraphs explain in turn, the coverage of contemporary statistics, estimates from academic stock models and the approach adopted within UK BIEC.

The ONS publishes regular statistics estimating the financial value of output of a range of building classes (ONS, 2015a); however this does not include associated floor area. Floor areas are included in planning applications, but submitted areas are not amalgamated or reported. In any case, a total derived from addition of successful planning applications would not be expected to match the as-built total, owing to later changes in design and the number of projects for which permission is granted but construction does not proceed. The Valuation Office Agency (VOA) provides statistics on the hereditament floor area and rateable value of property liable for business rates for the period 1998-2008 (DCLG, 2012). These are divided into retail premises, commercial offices, 'other' offices, factories, warehouses, other bulk premises and non-bulk premises. Statistics for the period until 2012 are also available, though only for four categories of 'Retail', 'Offices', 'Industrial' and 'Other' as part of an 'experimental' statistical release. A comparison of these two releases indicates a discrepancy for the total 2005 rateable stock of some 29,148,000 m^2, indicating the level of uncertainty even in Government databases. Revaluation of properties occurs on a five yearly cycle (recently 2000, 2005, and 2010). The VOA data does not reveal the demolish/rebuild cycle or indicate the extent of change of property use but does give some indication of the magnitude of stock within each class and the general trend (i.e. expansion or decline in stock).

This problematic lack of non-domestic floor areas was also encountered by the authors of the GCB Routemap who commented that "*a better understanding and publication of non-domestic floor areas by occupancy would in future benefit further, more detailed analysis*" (GCB, 2013b p. 32). Indeed, the need for more reliable models of the composition and dynamic of the non-domestic building stock has been widely recognised by academic authors, and has been the subject of a growing body of research over the last 25 years (Kohler et al., 2009). Work conducted by Harry Bruhns and colleagues in the early 1990s (Isaacs & Steadman, 2013), culminated in publication of the first estimate of the UK non-domestic building stock for 1993/94 (Bruhns et al., 2000). The Bruhns estimate was based upon a painstaking process of combining and reclassifying a variety of data sources including the VOA statistics, surveys of four English towns and a wealth of class specific publications. The resultant Non-domestic Building Stock Database (NDBSD) was used to assess operational carbon reduction potential as part of the CaRB and CaRB2 projects at UCL (UCL, 2013). It also formed the basis for the N-DEEM (Non-domestic Energy and Emissions) model maintained by the BRE. The latest NDBSD version provides an approximate snapshot of the 2012 non-domestic stock. Other authors have attempted to integrate the VOA data with Ordnance Survey Master Map building polygons to assess the non-domestic stock at the urban scale (Taylor et al., 2014). However, this work remains ongoing, owing to the complexity of combining these sources into self-contained units appropriate for subsequent modelling. In short, current non-domestic building stock models still consist of snapshots based on limited data and do not track annual new additions or reductions in stock.

In the absence of access to reliable statistics or an independent model, it was necessary to establish a methodology for estimating annual additions to stock for each class. The adopted approach combines the financial value of output published by the ONS with historic price data obtained from industry standard price books. This is similar to the approach adopted by Doran (2014), though it is subject to a number of minor improvements and applied to a broader array of building classes. Prices were obtained from numerous past editions of the Spon's Architects' and Builders' Price Book (AECOM, 2015b) which provides estimated costs for a wide variety of building types per square metre. A decision was made to base prices for each year on past price book editions rather than simply deflating from current prices using general figures, such as the CPI or the Government's Construction Output Price Indices (BIS, 2015). The past decade was a particularly turbulent period for the industry with severe fluctuations in raw material and energy prices, and many high profile changes to regulatory standards and client requirements. These changes affected each building class in fundamentally different ways; consequently applying generalised inflation figures would not capture these dynamics and result in poor estimates of price and floor area. As the particular mix of new buildings within each class was unknown it was necessary to assume that they were broadly in line with the proportions of the existing stock, according to the Bruhns estimates. Where the dominant form of building within each class was a particular building type, this was used as a representative average price for the sector. Where new build within a class is composed of a diverse range of building types, an average price was calculated based upon prices for multiple building types and their approximate share of the existing stock. By this means estimates of new build floor area for each building class for 2001-2013 were established (see Figure 25). See Appendix D for detailed consideration of each building class and comparison with the VOA statistics.

Figure 25: Estimated annual new build floor areas by building class 2001-2013



6.3.4 Initial bottom-up estimate

The carbon intensity function of each building class is scaled to the output profile for each year and the total embodied carbon associated with producing that output is calculated. In the case of 'miscellaneous' buildings and 'infrastructure' the bottom up estimates are calculated directly by multiplying the financial value of output by the carbon intensity per £ of output from the WRAP Resource Efficiency Benchmarks. These ten bottom-up estimates cumulatively amount to less than the top-down sector totals from the UK MRIO model. This is to be expected for two reasons. Firstly, the building level LCAs in the database suffer from truncated system boundaries and the other shortcomings described in Section 2.4.2.4. Secondly, the entries in the database are likely to represent better than average examples of each class, as practitioners that conduct embodied carbon assessments and disseminate their results are more likely to seek to minimise embodied carbon in their designs. For the model run reported in the following sections, the discrepancy between bottom-up and top-down totals for each year is between 20-40%. Thus a calibration process is required to correct for this discrepancy.

6.3.5 Model calibration

The calibration process is applied in two steps. Firstly, the difference between the top-down total and initial bottom-up total is distributed between the building classes in proportion to their share of the initial bottom-up total. Thus each class has a new target total. The code then x-shifts the carbon intensity function by increments of 1 $kgCO_2/m^2$ and produces a new bottom-up total. This process is looped until the bottom-up total is within 1% of the target total. The results of this calibration can be seen in Figure 26.

This process inherently assumes that the absolute difference between the reported embodied carbon figures and the true embodied carbon figures is the same on all projects. It is more likely that there are similar proportional differences. However, implementing a calibration loop that worked upon this alternate assumption would significantly increase complexity. Given the inaccuracies in the underlying data and assumptions, a simple calibration process was deemed appropriate. Using this calibration process a baseline time series of embodied emissions in the construction sector by building class was produced (see Figure 27 overleaf).

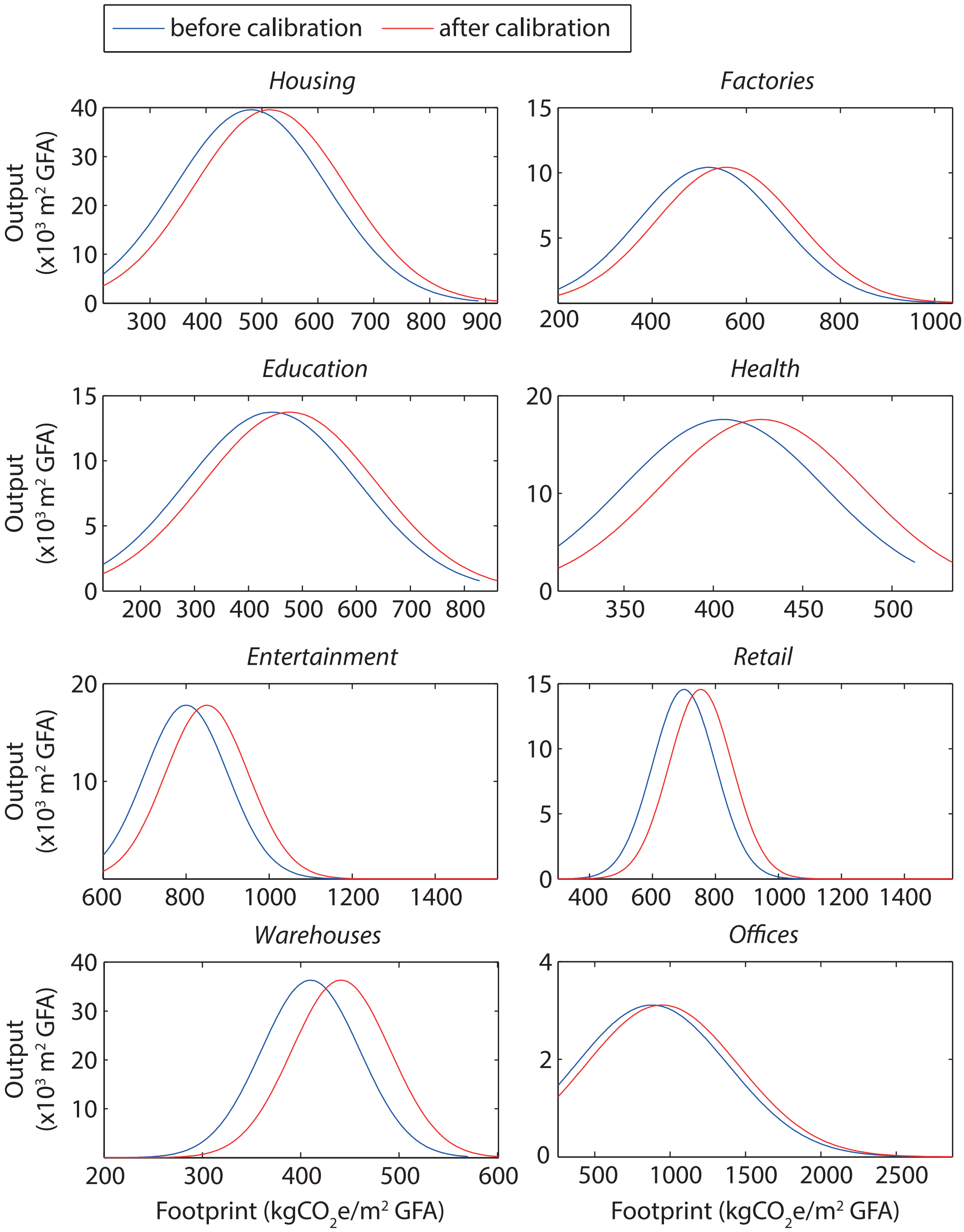
6.3.6 Scenario analysis

The scenario analysis was conducted in two phases. First, a series of plausible projections of future demand for buildings of each class were prepared, and the associated aggregate emissions enumerated. Secondly, required improvements in carbon intensity to meet sector targets and the impact of possible regulations were then considered through implementing changes in the carbon intensity functions of each class. The following sections consider these two phases in turn. It should be noted that the demand projections assume no additional policies are introduced to explicitly restrict demand for stock or address embodied carbon.

6.3.6.1 Future demand projections

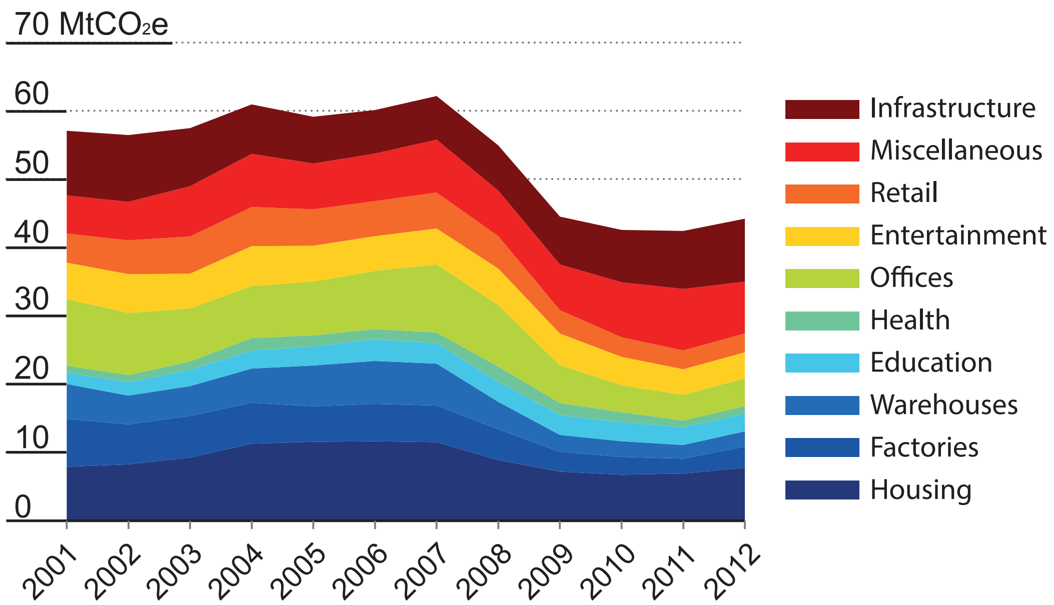
When establishing projections of future additions to the building stock, two approaches were considered: the adoption of existing independent projections; or the development of novel scenarios. The first approach was briefly investigated then discarded owing to the lack of detailed independent projections. A number of organisations provide 3-year industry forecasts with varying degrees of granularity

Figure 26: Model calibration - 2011 carbon intensity functions



(Construction Products Association, 2015; AECOM, 2015a; Experian, 2015). However, owing to the volatile nature of the industry, few analysts attempt to make long term forecasts (>5 years). In such instances, these are generally restricted to very high level forecasts, such as the Global Construction series, currently providing estimates to 2025 (Global Construction Perspectives & Oxford Economics, 2013). Unfortunately, such estimates do not disaggregate beyond infrastructure, domestic and non-domestic properties. This problem was also encountered by the GCB Routemap authors, who developed an independent set of growth factors shown in Table 15. The Routemap projections of domestic stock were simply based upon an assumed growth rate of 1% and an assumed demolition rate of existing buildings of 0.1% (GCB, 2013b p. 31). Routemap growth rates for non-domestic stock were established from historic trends in the VOA data, whilst growth in infrastructure was extrapolated from long run trends in the ONS output statistics. According to the Routemap authors, this simplistic approach was adopted owing to the project time constraints. The approach was subject to criticism, as, for example, the National Infrastructure Plan already sets out an increase in road building which goes beyond the 0% growth rate assumed in the GCB model. A further attempt to estimate long term stock additions was made as part of a BRE project assessing the comparative cost and CO_2 savings of energy efficiency measures in new and existing buildings (MacKenzie et al., 2010 p. 14). The authors estimated an additional 8 million domestic properties and 400 million m^2 of new build non-domestic properties would be produced by 2050. Unfortunately these figures were not disaggregated and the underlying assumptions were not made open to public scrutiny. Thus as no robust, independent, disaggregated projections could be sourced, it was necessary to establish novel projections of new build.

Figure 27: Calibrated embodied carbon emissions by building class from UK BIEC model



Demand in the construction industry is dependent upon a number of interconnected variables. At a sector level it is strongly correlated with the growth of the national economy and the overarching financial climate, with investor confidence typically reflected in new orders. Demand also responds in the long term to demographic trends, such as changes in the size, age and geographical distribution of the population. Long run structural changes in the economy, for example the shift from manufacturing to a service economy, also profoundly influence the type of structures produced. National and local changes in planning policy and building regulations similarly affect the volume and type of construction undertaken. Government interventions in the market, such as the Help to Buy Scheme, can further influence demand. Demand for new properties is also dependent on rates of demolition and refurbishment of older properties. Similarly the viability of changing building use is determined by numerous factors. Incoming Government policy, such as the introduction of Minimum Energy Performance Standards, may shift the balance between demolition and refurbishment over the coming decades. All of these interconnecting factors contribute to determining the future demand for building and infrastructure stock and the way in which that demand will be met. Determining future demand for stock is thus dependent on multiple interdependent variables. In an attempt to simplify this complex system, projections were simply based upon changes in three key variables: population; economic growth; and infrastructure investment. 27 demand projections, labelled A-ZZ, were made based upon a range of values for these three variables (see Figure 28 overleaf). Projections

Table 15: Assumed growth factors in GCB Routemap scenarios (GCB, 2013)

Class	Annual growth rate to 2050
Buildings	
Domestic	0.9%
Retail	0.6%
Commercial offices	2.7%
Non-commercial offices	0.3%
Industrial	-0.2%
Other	1.5%
Infrastructure	
Water	3.2%
Sewerage	0.6%
Electricity	9% to 2017, 1.2% post-2017
Roads	0.0%
Railways	1.7%
Harbours	0.0%
Aviation	1.3%
Gas	1.3%
Communications	1.3%

of population, households, and economic growth are shown in Table 16 and Table 17. All projections are taken from respected sources and represent the central range of plausible futures. The data sources for each projection are summarised in the following paragraphs.

Economic Growth

Central projections of short term economic growth were taken from OBR forecasts of annual GDP growth to 2019 (OBR, 2015). Long term projections beyond 2019 were taken from the OBR's 2012 Fiscal Sustainability Report (OBR, 2012). Alternate projections for high and low growth scenarios were estimated assuming trends in line with the typical discrepancies between highest and lowest forecasts published in HM Treasury's regular review of independent forecasts for the UK economy (HM Treasury, 2015b).

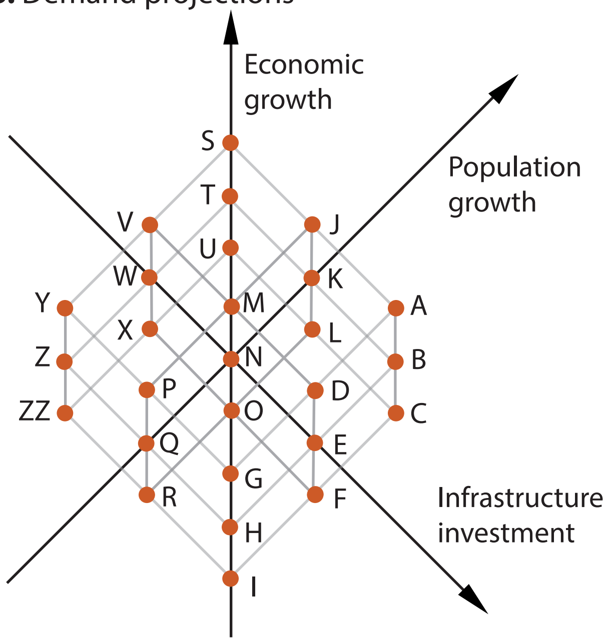
Population

Population projections were taken from the ONS' 2010-based national population projections (ONS, 2011). The ONS provides 9 alternative projections based upon varying assumptions about fertility, life expectancy and migration. Three of these projections were used in the scenarios: HP (high fertility, high life expectancy, high migration); P (principal projection); and LP (low fertility, low life expectancy, low migration).

Households

DCLG projections assume a gradual decline in the average household size from 2.36 people in 2012 to 2.25 people by 2030 (DCLG, 2015b). Combined with other demographic trends, this results in a central projection of households as shown in Table 17. High and low projections of likely housing demand attributable to population growth were calculated by combining the ONS's high and low population estimates with the average household size projections. However, as can

Figure 28: Demand projections



be seen from the current housing crisis, growth in supply does not directly respond to demographic demands. Therefore low and high scenarios for housing construction were developed that correspond to a continued failure to meet demand and, by contrast, a successful reduction of the existing housing shortage. The high projection assumes that it will take 3 years to return to house building levels that meet the highest anticipated annual increase in population, and subsequently increases to clear the estimated housing shortage by 2030. The low projection assumes that it

Table 16: Projections of economic growth

	Low growth	OBR forecast	High growth
2013	1.7%	1.7%	1.7%
2014	2.6%	2.6%	2.6%
2015	2.1%	2.5%	3.0%
2016	1.9%	2.3%	2.8%
2017	1.9%	2.3%	2.8%
2018	1.9%	2.3%	2.8%
2019-2020	1.9%	2.3%	2.8%
2021-2030	2.0%	2.4%	2.9%

Table 17: Projections of population and households (millions)

	LP*	P*	HP*	Number of households in central scenario
2012	63.070	63.244	63.373	26.729
2013	63.405	63.758	63.999	26.956
2014	63.718	64.271	64.638	27.210
2015	64.017	64.776	65.285	27.468
2016	64.306	65.271	65.934	27.735
2017	64.582	65.755	66.578	27.996
2018	64.855	66.232	67.223	28.256
2019	65.124	66.705	67.869	28.515
2020	65.390	67.173	68.515	28.771
2021	65.652	67.636	69.159	29.026
2022	65.907	68.092	69.800	29.276
2023	66.155	68.539	70.436	29.523
2024	66.394	68.976	71.067	29.771
2025	66.622	69.404	71.692	30.015
2026	66.839	69.820	72.311	30.263
2027	67.044	70.226	72.925	30.506
2028	67.237	70.623	73.535	30.746
2029	67.416	71.011	74.141	30.982
2030	67.582	71.392	74.743	31.213

* HP is high fertility, high life expectancy, high migration ONS projection
P is principal ONS projection
LP is low fertility, low life expectancy, low migration ONS projection

will take 7 years to return to house building levels that meet the lowest anticipated increases in population, and no attempt is made to address the existing shortage. The central projection assumes that it will take 5 years to return to house building levels that meet the central estimates of population increases.

Non-domestic stock

The variable upon which each non-domestic building class has been made dependent is summarised in Table 18. The particular projections for each class are explained in the following paragraphs.

Output of warehouses, factories and miscellaneous buildings were assumed to follow trends in economic growth. Output in the entertainment class has remained fairly consistent for the preceding 17 years for which data is available, so the central projection continues average output from 1998-2012. High and low projections assume a slow return to the highest and lowest levels of output observed during this period. Over the same period, a 10% increase and a general ageing of the UK population has resulted in a 60% increase in output of new buildings for healthcare. The central scenario assumes this trend continues with the additional growth in expenditure proportional to population growth.

Projections for the education class assume that recent output represents the ongoing replacement rate of stock and that additional demand for stock will be due to population growth. Anticipated trends in the total number of school pupils have been used as a proxy, with the assumption that new build schools will accommodate the same density of pupils per unit area.

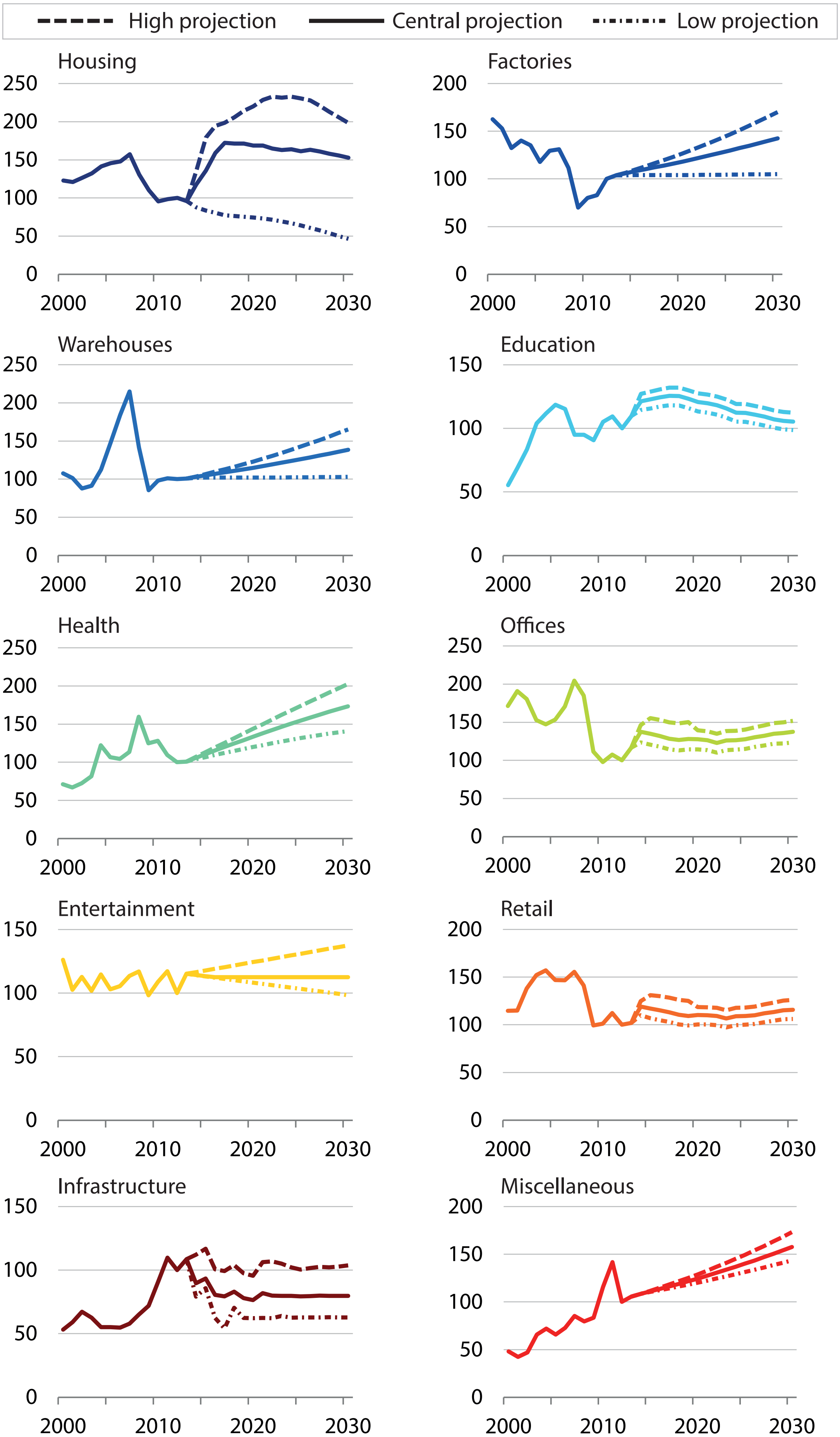
For offices and retail, the future working age population was estimated from the ONS population and age distribution projections. By assuming a continued employment rate of 73.3% to 2030 the expected annual increase in the UK workforce was calculated. The central scenario assumes that 50% of this additional workforce will work in offices and 10% will work in retail, similar to the current distribution of UK employment. The requisite increases in floor area to accommodate these additional workers were estimated based upon an assumed worker density of 10.9 m^2/worker for offices and 35 m^2/worker for retail (BCO, 2013). High and low scenarios reflected the expected changes in workforce under the HP and LP population scenarios.

High, low and central projections for each class are summarised in Figure 29. The variation in range between high and low scenarios for different classes reflects the relative predictability of demand within each class, whilst the varying shapes of the curves reflect the differences in underlying assumptions between classes.

Table 18: Demand projection variables and dependent building classes

Variable	Dependent building classes
Economic growth	Factories, Warehouses, Entertainment, Miscellanous
Population	Housing, Education, Health, Offices, Retail
Infrastructure investment	Infrastructure

Figure 29: Demand projections by class (indexed to 2012 output = 100)



Infrastructure

The UK's National Infrastructure Pipeline (NIP) sets out an overview of planned and potential UK infrastructure investment to 2020 and beyond (HM Treasury, 2014). The 2014 NIP anticipates public and private investment of £466,031 million from 2014/15 to post 2020/21. This represents expenditure of the order of £50 billion per annum. However, it is unlikely that investment and approval will be secured for all projects in the pipeline. At the time of writing, of the £466,031 million of desired investment only £196,208 million was assigned to projects that are active, approved or in construction. Three scenarios for infrastructure development were thus established: low, medium and high investment.

The low scenario assumes investment until 2016 corresponding to the investment across NIP projects under construction at the time of writing, followed by an extension of average investment for 2014-2016 until 2020, with a rolling 5 year average thereafter. The medium investment scenario assumes that 80%* of desired investment set out in the NIP is achieved til 2020, with a rolling 5 year average thereafter. The high investment scenario assumes all desired investment in the NIP is achieved til 2020; with additional projects contributing to a sustained high level of infrastructure expenditure beyond 2020, similar to average levels observed between 2012 and 2017.

It should be noted that the NIP employs a much broader definition of 'infrastructure' than that used by the ONS. The NIP definition includes non-construction measures such as the roll out of smart meters, introduction of ticketless payment schemes on public transport and the replacement of rolling stock. The NIP definition also fails to distinguish between expenditure on new work and repair and maintenance. The ONS publish data evaluating infrastructure output in the construction industry as far back as 1955. However, comparable time series data for the definition of infrastructure utilised in the NIP do not exist. As the NIP and ONS figures are not directly comparable adjustments have been made to the scenario values. The adjusted expenditure series was produced by multiplying future NIP expenditure (in 2013 prices) by an adjustment factor based upon the ratio between the 2013 ONS output for new work in infrastructure and the 2013 NIP expenditure.

Thus using different combinations of economic growth, population growth and infrastructure investment 27 alternate demand projections were established.

6.3.6.2 Projected grid decarbonisation

The carbon intensities of UK and international electricity grids are expected to significantly reduce over the analysis period as existing plant is replaced with low carbon alternatives. Consequently, it is essential to incorporate this improvement

*Retrospectively comparing anticipated investment for 2013 from the first edition of the National Infrastructure Pipeline with recorded investment for the period reveals that just under 80% of anticipated investment was achieved.

into future projections. A decomposition analysis of the UK MRIO reveals that in 2011, 22% of the UK construction sector's embodied carbon footprint was attributable to electricity. Using this data and projected improvements in UK electricity emission factors from DECC (see Table 19) potential reductions in construction sector embodied emissions attributable to improvements in grid intensity were projected.

It should be noted that a portion of this footprint is associated with overseas electricity grids. To avoid the complexity of determining grid projections for each foreign supplier, it has been assumed that all countries make equal proportional improvements to the UK. As it is impossible to determine from the available data the proportion of each building class' footprint that is attributable to electricity, reductions have been applied uniformly across all classes. A future version of the model would benefit from enumerating the differing contributions of electricity to each class. This could be estimated from a detailed analysis of a sample of building LCAs from each class.

Further improvements in major material production processes are also anticipated over this timeframe (as discussed in Section 3.5). However, preliminary calculations suggest that anticipated contributions (predicated on the achievement of stated steel and cement industry targets) would not yield greater than a 2% reduction in total construction sector embodied emissions over the scenario

Table 19: Projected generation-based grid average electricity emissions factors (DECC, 2014)

	Generation-based grid average ($kgCO_2e/kWh$)	Indexed to 2012
2012	0.493	100
2013	0.460	93.2
2014	0.461	93.4
2015	0.433	87.7
2016	0.338	68.6
2017	0.326	66.0
2018	0.307	62.3
2019	0.266	53.9
2020	0.238	48.2
2021	0.213	43.3
2022	0.197	40.0
2023	0.187	37.9
2024	0.166	33.8
2025	0.150	30.5
2026	0.126	25.5
2027	0.116	23.5
2028	0.102	20.8
2029	0.105	21.3
2030	0.102	20.7

timeframe. Therefore these anticipated improvements have been omitted from explicit analysis within the model. In the unlikely event that more radical targets are adopted, this decision could be revisited.

6.3.6.3 Targets for comparison

To place the demand projections in context it is necessary to compare them with stated carbon reduction targets. Two sets of targets are considered: the interim targets for embodied carbon reduction from the GCB Routemap and the relative share of the UK Carbon Budgets attributable to the construction sector. The headline 50% carbon reduction target from Construction 2025 was also considered as a potential point of comparison; however, as it is expressed as an aggregate target for all emissions from the built environment, it cannot be interpreted as a specific target for embodied carbon.

Routemap Interim Targets

The first Routemap interim target is a 21% reduction by 2022 against a 2010 baseline, equivalent to achieving capital carbon emissions totalling 26.6 MtCO_2e. Further suggested targets included 29% by 2027 (23.9 MtCO_2e), 34% by 2037 (22.2 MtCO_2e) and 39% by 2050 (20.5 MtCO_2e). A further reduction attributable to installation of carbon capture and storage on all steel and cement facilities lowered the 2050 total to 11 MtCO_2e. However, the Routemap interim targets were set against a 2010 baseline of 33.6 MtCO_2e for capital carbon emissions. The UK BIEC model estimates embodied emissions in 2010 to be 42.5 MtCO_2e. Therefore an adjustment of the reduction targets is required to ensure consistency. Taking the UK BIEC embodied emissions estimate alongside domestic, non-domestic and infrastructure operational carbon emissions of 103, 48.2 and 5 MtCO_2e respectively (as estimated in the Routemap), then total emissions from the built environment amounted to 198.7 MtCO_2e in 2010. Assuming that the Routemap targets for domestic and non-domestic operational carbon are achieved then embodied emissions would need to reduce to 16.5 MtCO_2e by 2050 to achieve the sector's ambition of an 80% reduction against a 1990 baseline. This translates into interim targets of 33.6 MtCO_2e for 2022, 30.2 MtCO_2e for 2027 and 28.0 MtCO_2e for 2037.

UK Carbon Budgets

An alternate approach to aiming for interim annual targets is to compare cumulative emissions over the analysis period with the UK's 5-year carbon budgets. The carbon budgets are expressed in absolute terms and as reductions against a 1990 baseline, when UK territorial emissions were 809.4 MtCO_2e. As the UK BIEC model considers consumption-based emissions it is necessary to scale the budgets for a fair comparison. However, estimates of the UK's consumption-based footprint are not available before 1997. Therefore the percentage reductions have been translated into reductions against a 2012 territorial emissions baseline of

582.2MtCO_2e. These reductions were applied to 2012 consumption based emissions of 863.9 MtCO_2e to establish a set of equivalent consumption-based carbon budgets (see Table 20 overleaf). It should be noted that this approach implicitly assumes that the ratio between territorial and consumption based emissions remains the same as in 2012. This ratio has varied historically, falling year-on-year in 5 of the last 14 years and rising in the remaining 9. It is unclear how this ratio may vary in future (Scott & Barrett, 2015). The results presented in the next section are expressed as relative proportions of these equivalent consumption-based carbon budgets.

6.3.7 Results

Results of the demand projections can be seen in Figure 30 and are summarised in Table 21 overleaf. The difference between the highest (A) and lowest (ZZ) projections represents additional annual embodied carbon emissions of 24.4 MtCO_2e by 2030, and cumulative emissions of some 333 MtCO_2e over the analysis period. Grid decarbonisation is expected to reduce these impacts, as shown in Figure 31 overleaf. Under the central projection (N) this would avoid annual emissions of 9.2 MtCO_2e in 2030 and 105 MtCO_2e over the analysis period.

When compared with the UK Carbon Budgets the highest projection (A) anticipates that embodied carbon in construction will grow from 5.1% of the 1st

Figure 30: Projected embodied emissions of UK construction 2001-2030 assuming no improvements in carbon intensity of electricity supply

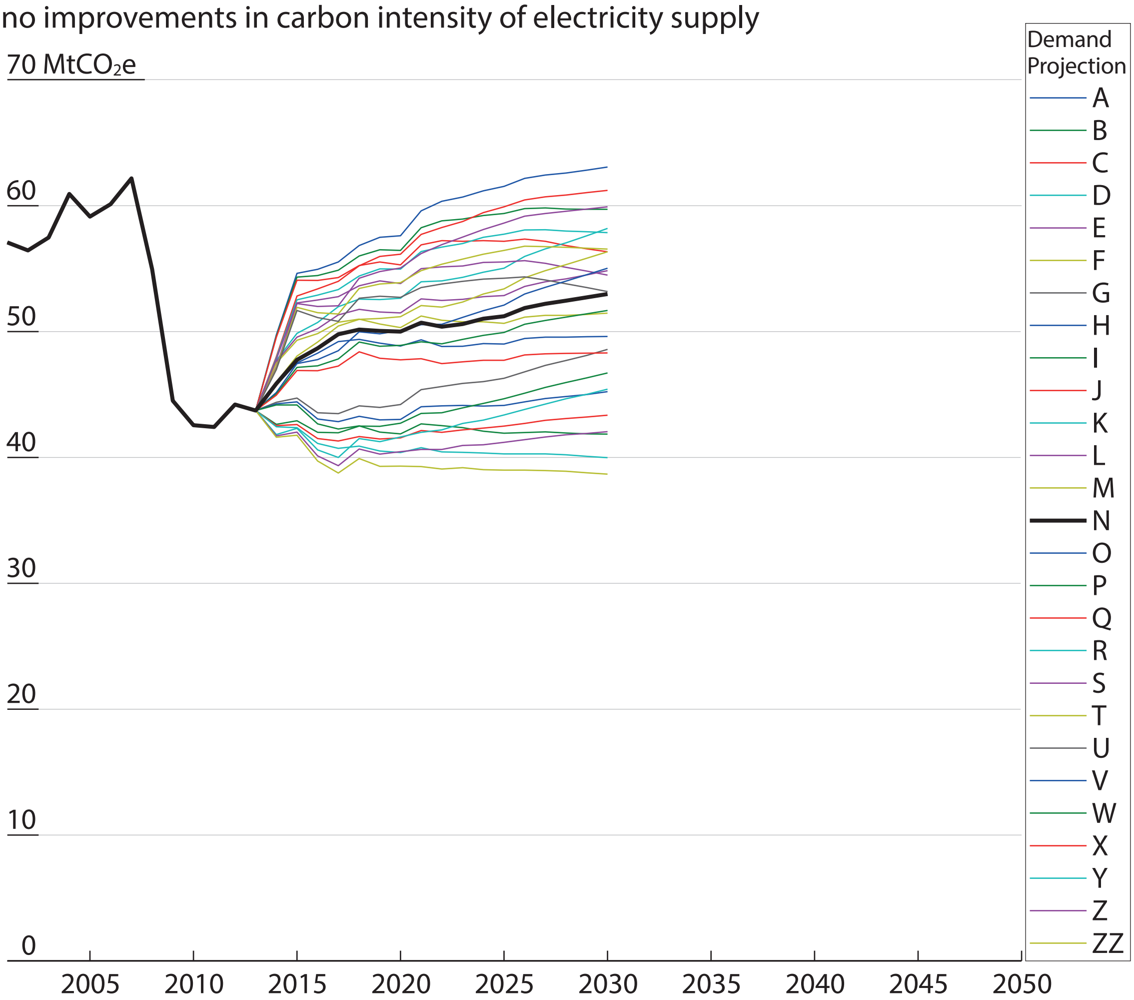


Table 20: UK Carbon Budgets and consumption-based equivalents

Carbon Budget	Budget level ($MtCO_2e$)	Reduction below 1990	Consumption-based equivalent budget ($MtCO_2e$)
1st Carbon Budget (2008-12)	3,018	23%	4,487
2nd Carbon Budget (2013-17)	2,782	29%	4,128
3rd Carbon Budget (2018-22)	2,544	35%	3,775
4th Carbon Budget (2023-27)	1,950	50%	2,894

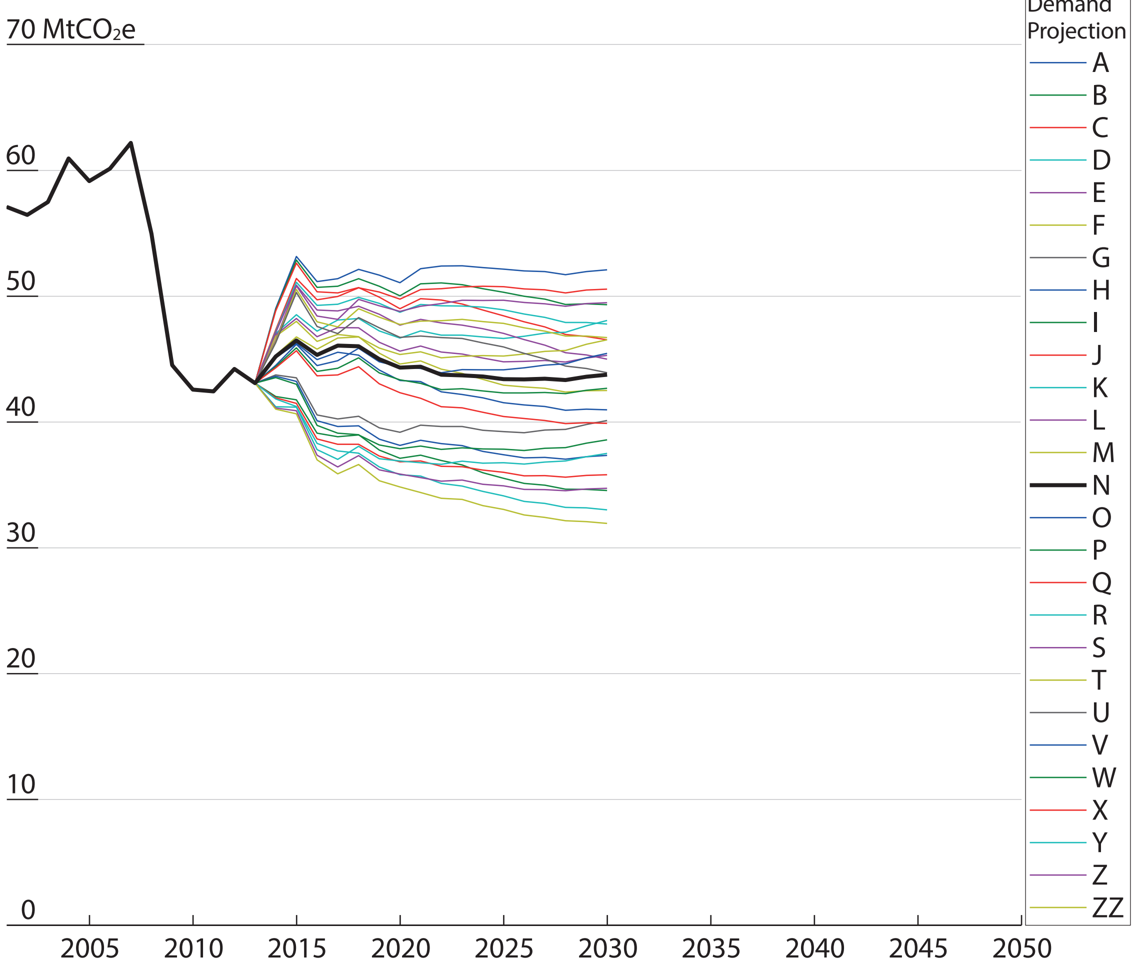
Table 21: Demand projection results ($MtCO_2e$). Anticipated grid decarbonisation included (Inc) and excluded (Exc).

Demand Projection	Annual emissions in 2022		Annual emissions in 2027		Annual emissions in 2030	
	Exc	Inc	Exc	Inc	Exc	Inc
A	60.34	52.38	62.44	51.93	63.07	52.07
B	58.79	51.03	59.81	49.75	59.71	49.29
C	57.22	49.67	57.16	47.54	56.34	46.51
D	54.02	46.89	56.57	47.05	58.19	48.04
E	52.46	45.54	53.94	44.87	54.83	45.27
F	50.90	44.18	51.28	42.65	51.46	42.48
G	45.64	39.62	47.30	39.34	48.57	40.10
H	44.08	38.27	44.68	37.16	45.21	37.32
I	42.52	36.91	42.02	34.95	41.84	34.54
J	58.25	50.57	60.70	50.48	61.21	50.53
K	56.70	49.22	58.08	48.30	57.85	47.76
L	55.14	47.86	55.42	46.09	54.48	44.97
M	51.93	45.08	54.83	45.60	56.33	46.50
N	50.37	43.73	52.20	43.42	52.97	43.73
O	48.81	42.37	49.54	41.21	49.60	40.94
P	43.55	37.80	45.56	37.89	46.71	38.56
Q	42.00	36.46	42.94	35.71	43.35	35.79
R	40.43	35.10	40.28	33.50	39.98	33.00
S	56.89	49.39	59.37	49.38	59.91	49.45
T	55.34	48.04	56.75	47.20	56.55	46.68
U	53.78	46.68	54.09	44.99	53.17	43.89
V	50.57	43.90	53.50	44.50	55.03	45.43
W	49.01	42.55	50.88	42.32	51.67	42.65
X	47.45	41.19	48.22	40.10	48.29	39.87
Y	42.19	36.62	44.23	36.79	45.41	37.48
Z	40.64	35.27	41.61	34.61	42.05	34.71
ZZ	39.07	33.92	38.95	32.40	38.67	31.92

Carbon Budget to 9.0% of the 4th Carbon Budget. This includes anticipated grid decarbonisation, without which it could rise to 10.6%. Under the lowest projection (ZZ), embodied carbon in construction represents 5.7% of the 4th Carbon Budget. Given the step change in national emission reductions anticipated under the 5th Carbon Budget it is likely that embodied carbon in construction will account for a sizeable proportion (>10%) of the available carbon space under all subsequent budgets.

Figure 32 overleaf compares the demand projections with the targets proposed in the GCB Routemap. Figure 33 presents a similar comparison incorporating anticipated grid improvements. It is clear from such a comparison that considerable additional improvements in building design, material manufacture and on-site activities will be required if these targets are to be met. These improvements must be made in addition to DECC's anticipated grid improvements and the widespread deployment of CCS in steel and cement manufacture assumed by the Routemap authors. If grid improvements do not occur at the expected rate, or CCS fails to become financially viable for material manufacturers, then the anticipated improvements required from designers would increase substantially. For example, under the central projection N, if CCS is assumed to make no contribution by 2050 and the

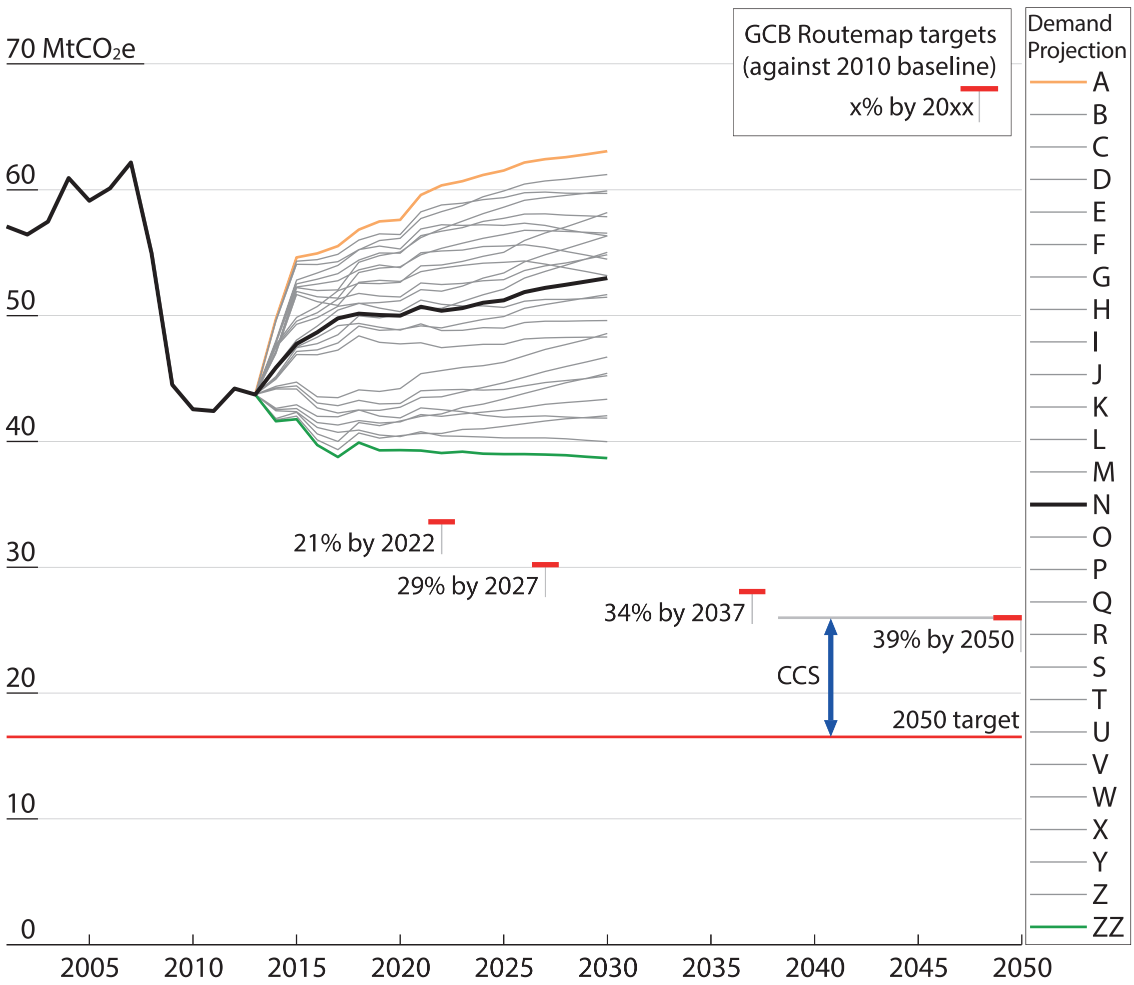
Figure 31: Projected embodied emissions of UK construction 2001-2030 including projected improvements in carbon intensity of electricity supply



grid remains at current carbon intensity, then meeting the 2027 Routemap target would require more than double the level of improvements from building design, material manufacture and on-site activities. From a designer's perspective this may necessitate a fundamentally different set of building materials and structural forms.

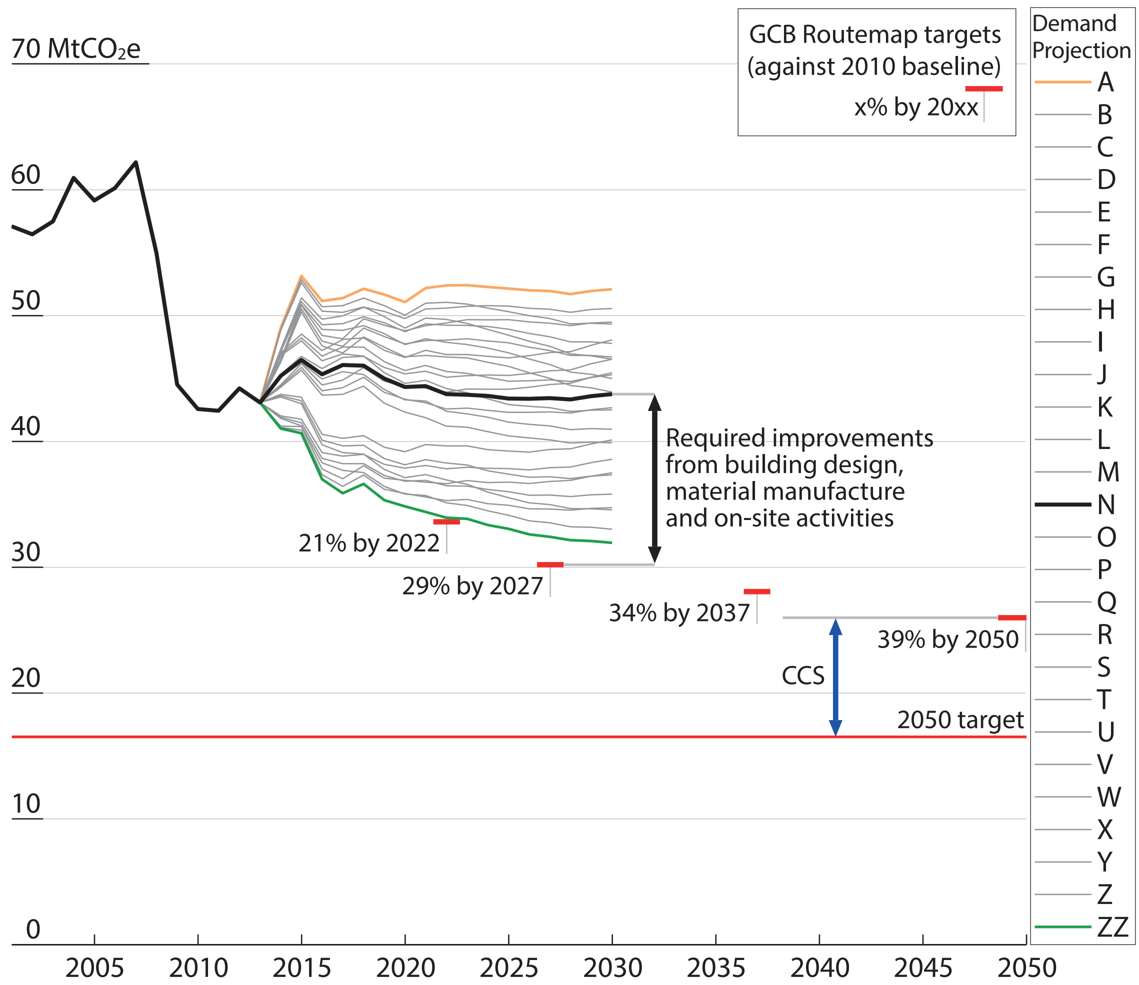
To further explore the implication of assumptions about the grid, CCS uptake and future demand for stock consider the following two extreme scenarios. First, if it is assumed that demand proceeds along the lowest projection (ZZ), anticipated improvements in grid intensity are achieved and CCS uptake matches the Routemap prediction, then at a project level designers need only achieve a 7% improvement in carbon intensity compared with current practice. This may well be achieved simply through the proliferation of current best practice in design and would not require fundamental changes in materials or structural forms. However, if, by contrast, demand proceeds along the highest projection (A), the carbon intensity of the grid remains at current levels and there is no CCS, then designers may be faced with the prospect of making 67% reductions in carbon intensity across all projects by 2027 if the Routemap targets are to be achieved. Such a high level of emissions reduction is likely impossible for certain building classes and would require widespread uptake of alternative materials and structural forms for other classes.

Figure 32: Projected embodied emissions of UK construction 2001-2030 assuming no improvements in carbon intensity of electricity supply - relative to targets



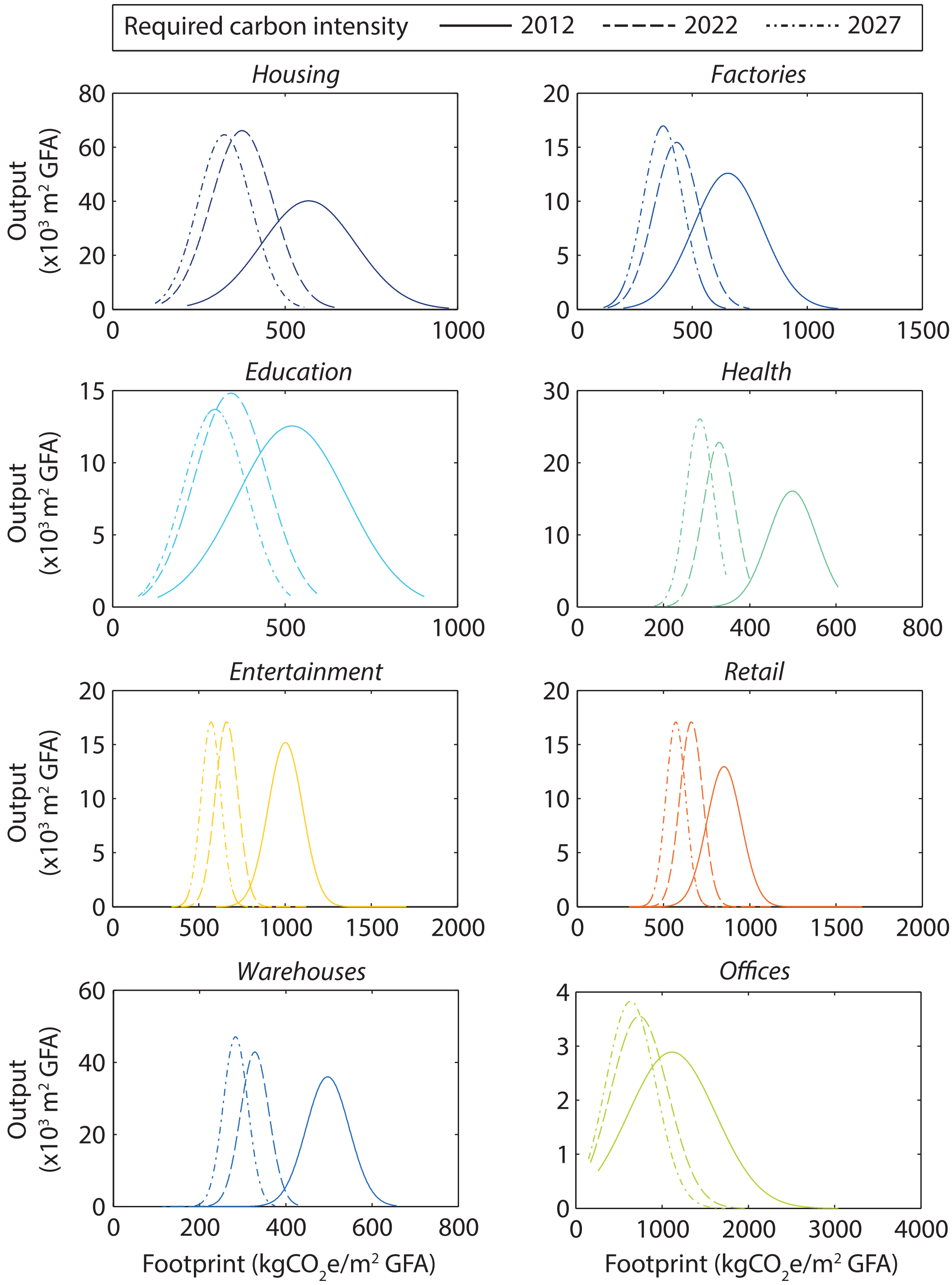
Regardless of the particular materials, technologies or policies adopted, ultimately these reductions must also correspond to a certain set of improved carbon intensity functions for each building class. For example, consider a scenario where demand follows central projection N and the burden of achieving reductions from design, material manufacture and on-site activities is distributed proportionally between all building classes, with all properties achieving similar proportional improvements. In such a scenario a new set of carbon intensity functions, shown in Figure 34 overleaf, must be achieved if the Routemap interim targets are to be met. Such a scenario would imply, for instance, that by 2027, 83% of housing must be built to the standards of the top 10% constructed today, and all new housing must be less carbon intensive than the current average. This could be considered a plausible ambition given 15 years to improve upon current practice. It becomes more achievable if the grid improvements anticipated by DECC are realised. For instance, Figure 35 overleaf, shows the equivalent carbon intensity functions of current housing under grid intensities anticipated in 2022 and 2027. This indicates that improvements in design would still be required but the changes need not be as substantial. However, whilst the prospects for housing in this scenario appear plausible, other building classes are already highly optimised and may

Figure 33: Projected embodied emissions of UK construction 2001-2030 including projected improvements in carbon intensity of electricity supply - relative to targets



prove impractical or excessively expensive to construct to the required levels. For instance achieving typical warehouse footprints of only 300 $kgCO_2e/m^2$ may prove impossible. Therefore it is likely that other classes such as housing and offices may require even greater improvements. The potential limits to emissions reduction within each building class are unknown but could be investigated through a series of detailed case studies. By such means a set of absolute or practical limits could be determined and a plausible range of target carbon intensity functions developed. However, such detailed studies of the practical limits for each building class go beyond the scope of this thesis.

Figure 34: Required improvements in carbon intensity functions to achieve GCB Routemap interim targets under central demand projection (N)



This example scenario also assumes that the shape of the carbon intensity functions remains similar over time. This implies the same proportional improvements in all properties. It may be that skewed carbon intensity functions emerge (see Figure 36) as designs approach certain physical limits or regulatory restrictions are imposed. For instance, if new building regulations required that embodied carbon be limited to a certain footprint per functional unit it is likely that there would be a large cluster of properties narrowly below that limit i.e. achieving compliance but not going substantially below the compliance limit. The scope of emission reductions from compressing the tail of current carbon intensity functions can be enumerated using the UK BIEC model. By this means the potential impact of particular regulatory limits upon aggregate emissions reduction could be assessed. Such a calculation with the model version presented here is unlikely to be accurate given the limited set of building classes and small sample of carbon assessments. However, with additional data and further disaggregation of building classes, the model could support this

Figure 35: Influence of electricity grid decarbonisation on carbon intensity function for housing under central demand projection (N)

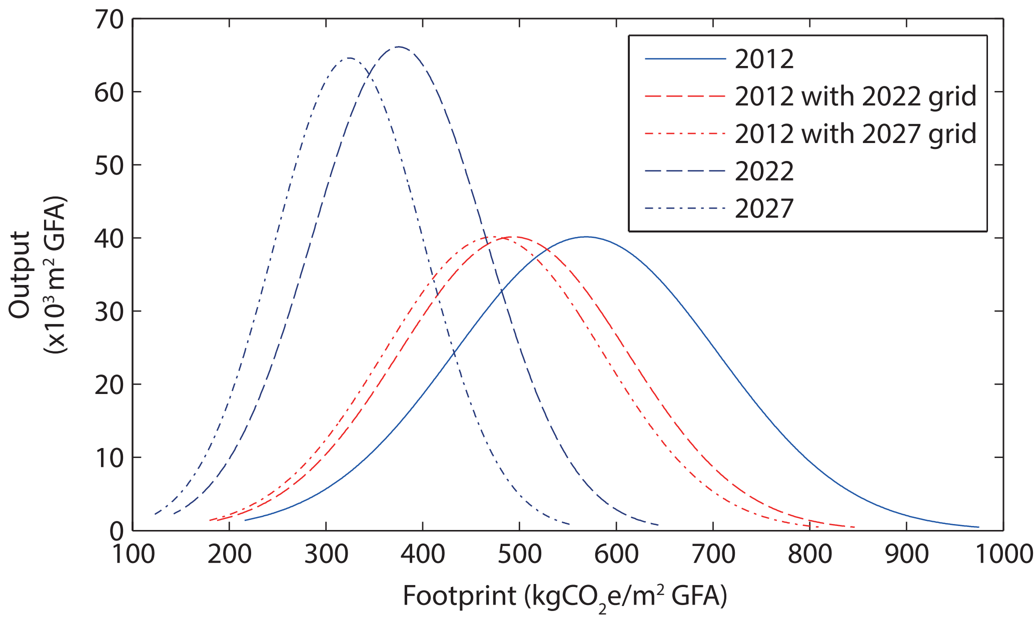
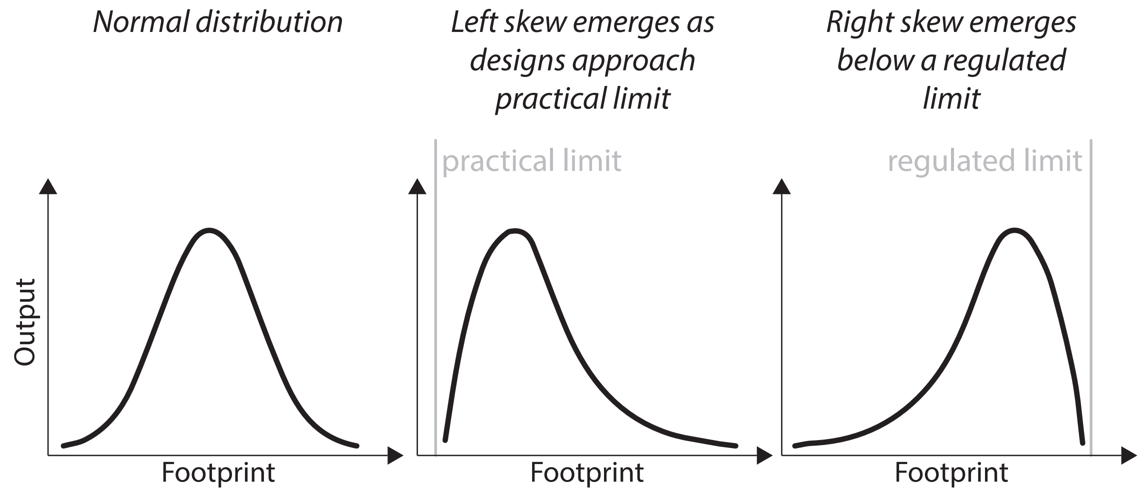


Figure 36: Possible changes to carbon intensity functions



sort of policy impact assessment. The obvious implication of introducing limits to the most carbon intensive properties is that a lesser improvement is required in typical and best practice properties to achieve aggregate targets.

Given a sufficient evidence base, the UK BIEC model could be used to simultaneously assess combined improvements in grid intensity, the introduction of regulatory limits, generic improvements in practice and the implications of practical design limits upon required emission reductions. As additional data becomes available, the model could also be used to chart progress towards targets, consider possible regulatory responses and provide indicative targets for designers that are consistent with national emission reduction targets.

6.3.8 Model limitations

The model suffers from a number of limitations that restrict the accuracy and range of applications. The following paragraphs set out these limitations, whilst the subsequent section describes intended model developments that may mitigate these concerns.

The model's core database of building level carbon assessments suffers from several shortcomings. Many of the carbon assessments are conducted to different standards, using different system boundaries and LCI datasets, preventing them from being directly comparable. Thus, a significant component of the difference between entries is likely to be the decisions made by LCA practitioners rather than differences in design and material selection. As industry approaches are increasingly standardised, comparisons between designs will become fairer. The small sample of building level assessments (249) used for the analysis presented here is also unlikely to be truly representative of sector output. The mix of project types for which LCA studies are conducted may also differ from the mix of project types built in each class. The projects on which LCA studies are conducted are also likely to represent the better end of the spectrum of current practice. Finally, the overall sample size is small relative to the number of structures produced annually in the UK. For certain building classes, the dependence upon published benchmarks is also undesirable.

Furthermore, in calculating output profiles for some classes the model depends upon estimates of physical output computed from economic data. This carries a substantial degree of uncertainty, although comparison between estimates of housing outputs using equivalent financial proxies and direct physical estimates suggests the difference may be minor. The top-down estimate of sector emissions also suffers from the typical limitations of an IO approach, discussed in Section 2.4.2.2.

The combined impact of these shortcomings is difficult to quantify and, consequently, it is advisable to view the results as being subject to a high degree of uncertainty. However, the magnitude of these errors is unlikely to be large enough to undermine the principal trends. Namely that additional improvements in building design, material manufacture and on-site activities will be required to meet the Routemap interim targets and that the range of materials and forms adopted in future will depend heavily upon the rate of grid decarbonisation, the uptake of CCS and the overall level of demand for new stock. In its current form the model essentially demonstrates a means to link sector level targets with project level targets using the best available data. As more data is gathered, the model will be opened to a wider range of applications and results will command greater confidence.

6.3.9 Future model developments

A number of further developments to the model and the underlying datasets could address these limitations, improve the model accuracy, and allow for additional applications.

The addition of more building carbon assessments will improve the representation of sector output, resulting in more accurate carbon intensity functions. Particularly crucial is the addition of LCAs for certain building classes with small samples, namely entertainment and factories, as this would allow for the replacement of benchmark data. A number of large construction firms have already committed to voluntarily upload results of all embodied carbon assessments to the WRAP database (Battle, 2014). The increasing standardisation of approaches to measurement and reporting of embodied carbon and the use of a more consistent set of LCI data sources should also reduce the error introduced from comparison of the LCAs. An alternative approach to circumvent this problem is to gather material quantities in isolation and conduct direct comparison with a common LCI database. This approach is currently being pursued by the authors of the ECQO database compiled at MIT (Ochsendorf & De Wolf, 2013). However, at the time of writing, the ECQO database contained a small sample of buildings from a range of countries with vastly different climactic conditions.

Further disaggregation of the building classes would allow designers to make more direct comparisons with model entries and projections. The ultimate goal would be to divide the model into a large number of discrete sub-classes that are familiar to designers. For instance, 'housing' would be divided into detached, semi-detached, mid terrace, end terrace and so on. Each sub-class would require the collection of a sufficient number of carbon assessments for the database to meet user requirements. The model could then be implemented with a hierarchical structure, whereby sectors that were not of specific interest to the user could be computed at an aggregate level, with sectors of interest disaggregated by sub-class. The user could then produce demand projections based upon their choice of assumptions and understand the implications for their designs. This could take the form of a set of interim targets for the relevant building sub-class which are consistent with the Routemap targets.

Further disaggregation of the infrastructure class in particular would greatly improve the model's detail and accuracy. As certain sectors of the infrastructure industry (such as water and sewerage) undertake more detailed carbon assessments and submit projections of future emissions to regulators (in this instance Ofwat), there is scope to incorporate this information into the base model and demand projections. The underlying ONS output data is already disaggregated by a number of infrastructure classes. This could be similarly matched with LCA data if a sufficient sample of projects were to be gathered. At the time of writing, discussions into development of a common repository of infrastructure LCA data comparable to the WRAP buildings database were ongoing.

Better statistics on physical industry outputs – i.e. completed floor areas – could remove the dependence on financial proxies for output. This information could perhaps be gathered and reported by district level planning authorities. Alternately approximate figures could be gathered by the respective industry institutes or membership organisations that represent each class e.g. the British Council for Offices, the British Council of Shopping Centres and so on.

Such changes could open up the model to a range of applications. Firstly, annual data could be used to monitor progress towards sector carbon reduction targets. Secondly, if classes were sufficiently disaggregated it would be possible to generate future embodied carbon targets for design teams that were consistent with sector and national reduction targets. This would allow designers to anticipate the sorts of materials and designs that may be required in future and to develop skills accordingly. Similarly, product manufacturers could develop solutions that would be compatible with these targets. A further disaggregated model could also facilitate impact assessment of potential policy interventions.

6.4 Discussion

The modelling exercise outlined in the preceding sections highlighted three sources of uncertainty that fundamentally impact upon the changes in design and practice that are required from construction practitioners over the coming decades. These relate to the rate of grid decarbonisation, the uptake of CCS, and the overall demand for new building stock. All three of these factors are beyond the control of designers and contractors, yet the response required from them to meet strategic emission reduction targets, such as those in Construction 2025 and the GCB Routemap, differs substantially depending upon the assumed changes in these factors. Thus, whilst the targets are absolute, the scale of response required from the industry is deeply uncertain. In such an environment it is difficult for practitioners and educators to anticipate the range of technologies, materials and practices that may need to be adopted and to develop appropriate skill sets. These multiple sources of uncertainty also make it difficult to propose policy solutions that are consistent with national carbon reduction targets. The implications of this deep uncertainty upon policy making is further explored in Chapter 7.

The scenario analysis also highlighted the need for radical options under the more challenging scenarios. For instance, if demographic trends require high levels of new building and CCS fails to become financially viable, then design teams may have to consider fundamentally different structural forms, material selection and so forth. The research community must start to consider what options could deliver a >50% embodied carbon reduction in certain structure types. If such radical reductions were required, what design changes and trade-offs would be palatable? Could, for example, the size of buildings be reduced (i.e. floor area or height)? Could occupant well-being and utility be preserved in smaller buildings that required fewer materials? Could radical changes in building form (e.g. greater use of shell structures) deliver substantive reductions in material use? Could demand for buildings be reduced by provision of more mixed use developments, with multiple end-user groups using the same structure? Would a fundamentally different material palette be acceptable to building end users? As radical responses may be required within the next two decades, the research community must start to consider such questions. This may require development of new technologies and design approaches; a better understanding (and perhaps reshaping) of user expectations; and the adaptation of ideas from other fields of climate mitigation.

For example, whilst a range of options promoting demand reduction have been considered as part of long-term energy decarbonisation targets (e.g. Pye, Usher, & Strachan, 2014; Toke & Taylor, 2007), comparable actions to reduce demand for new buildings and infrastructure have yet to be considered. Indeed, the current Government's priority is to "keep Britain building" (Osborne, 2015) apparently irrespective of the implication for carbon budgets. The deployment of low carbon technologies in energy provision, transport, and other key economic sectors heavily depends upon the widespread development of new infrastructure. However, the embodied emissions of these developments have yet to be considered in aggregate and the corresponding volume of repair and maintenance that is sustainable in the long term has yet to be determined. Even the GCB Routemap considers only a solitary set of demand projections for future stock, implying that this variable cannot be deliberated. At a global level, the potential folly of failing to consider the emissions embodied in infrastructure development has been highlighted by Muller et al. (2013), who demonstrated that the materials required for a globalization of Western infrastructure stocks could consume 35-60% of the remaining global carbon budget until 2050 if the average surface temperature increase is to be limited to 2°C. If the UK is to develop long term infrastructure plans that are consistent with progressively tighter carbon budgets, then the appropriate aggregate level of demand for new stock must be considered.

As the scenario analysis demonstrated, although the embodied emissions of buildings and infrastructure development makes only a modest contribution to current carbon budgets, it could occupy a sizeable proportion of the available carbon space by 2050. Beyond 2050 the process-based emissions associated with manufacturing key materials for infrastructure development and maintenance may dominate the remaining carbon space. Put simply, in the future there may be zero emission vehicles but there are unlikely to be zero emission roads. Therefore current plans for development of new infrastructure must also consider the embodied emissions implications of long term repair and replacement requirements within the context of future carbon budgets. Whilst current best practice considers embodied carbon at a project level, there has yet to be any serious consideration of the long term aggregate impacts of expanding and maintaining the UK's infrastructure stock within tightening carbon budgets. This debate is urgently required given the long lifetimes of buildings and infrastructure.

A further debate must focus upon the role of material producers within a low carbon economy. As UK production of bulk materials becomes less competitive and further significant investment in capacity appears unlikely, there is a strong likelihood that any increase in demand for materials will yield an increased dependence upon imports with greater carbon intensity. Such a transition could drive a greater rise in embodied emissions than is projected in the scenarios. Similarly, weak demand could yield further closures for domestic producers and increase dependence upon imports. The changes in demand implied by a partial shift to alternative materials and an absolute reduction in the use of carbon-intensive materials may necessitate a rebalancing of the UK materials market, which is likely to have profound impacts upon employment (Cooper et al., 2016). Few attempts have been made to quantify the structural changes, employment or emissions impacts of greater material efficiency upon economies (Nathani, 2010). This area urgently requires further research. Ultimately, a coherent long-term vision for material production and construction within a low carbon economy must be established such that the transition can be carefully managed.

6.5 Summary

As discussed in Chapter 2, embodied carbon reduction is most effectively delivered through the instatement of project carbon intensity targets. To date such targets have been based on relative comparisons with alternative buildings or designs. If sector carbon reduction targets are to be met, it is imperative that these overarching targets can be expressed as a series of absolute project carbon intensity targets. The UK BIEC model presented in this chapter provides, for the first time, a framework that links sector and project targets. The model is formed from a novel combination of top down and bottom up data sets and incorporates the best available data at the time of writing. Future expansion of the evidence base and further model development will increase accuracy and the range of applications.

A simple scenario analysis with the model illustrates the scale of the challenge facing the construction industry. The analysis highlighted the heavy dependence of the industry upon external actors to achieve sector carbon mitigation targets, through development of key technologies, such as CCS, and delivery of low carbon electricity. The required reductions at a project level are also highly dependent on aggregate construction output. Even if these external factors progress along the better end of Government estimates, the industry will still require modest changes in design, material selection and on-site practices in order to achieve interim targets throughout the 2020s. By contrast, if external factors are less favourable, then drastic changes in design may be required to deliver upon sector targets. If construction output progresses along the higher end of demand projections and CCS does not become financially viable for material producers then radical design solutions may be required by the late 2020s. This implies that the research community must begin investigating the feasibility and acceptability of ultra-low carbon designs.

The subsequent discussion further highlighted the potential role for demand reduction in the achievement of sector targets. Though demand reduction is often considered in other fields of climate mitigation, it has received minimal attention in the field of construction. Indeed, in this sector, any form of demand reduction may run counter to the prevailing political narrative which unambiguously supports increased output. The aggregate embodied carbon of proposed infrastructure development and long term maintenance requirements has yet to receive any serious consideration by researchers and policy makers. Indeed, even key models informing policy, such as NISMOD (Hall et al., 2013), only consider a limited subset of carbon incurred in the operation and use of key assets. Embodied emissions will undoubtedly constitute a growing share of the available carbon space as 2050 approaches and will require additional offsetting beyond 2050 if the long term net-zero emissions goal of the Paris Agreement is to be achieved. This implies that deliberations must now begin to determine appropriate long term levels of stock.

The discussion also highlighted the lack of a coherent vision for materials production within a low carbon economy. The likely impacts of reduced demand for key materials on industry structure and employment have yet to be evaluated. Effective management of the transition to a low carbon construction sector will require development of a coherent plan that considers both the role of demand for new stock and the impacts upon the materials supply chain.

It is clear that practitioners and policy makers face multiple sources of uncertainty making it difficult to distinguish the range of designs, materials and policy interventions that may be required under progressively tighter carbon budgets. The next chapter considers how to prioritise short term actions in the face of such uncertainty.

7. Policy pathways to reduce embodied carbon in the construction industry

> *The key risk to future progress is the current uncertainty over the long-term policy framework*
>
> Committee on Climate Change, 2015 Report to Parliament

7.1 Introduction

Chapter 6 demonstrated that significant reductions in embodied carbon will be needed to meet sector emission reduction targets. The surveys and interviews in Chapter 5 indicated that, in the absence of a compelling business case, substantive reductions will require additional policy drivers. As highlighted in Section 2.3.1, the last decade has seen a succession of short-lived climate mitigation policies that have excluded any explicit consideration of embodied carbon and failed to deliver adequate operational carbon reductions. This series of headline policies were heavily-trailed and did not suffer from a lack of ambition. However, the overarching policy framework appears to have been designed in a piecemeal fashion without due consideration for policy sequencing and adaptation. Unanticipated changes in the operating environment, including the recession and changes in Government, resulted in the sudden amendment or removal of the majority of mitigation policies in this sector, fundamentally undermining industry confidence. The failure to include any significant options for policy adaptation or a clear exit strategy for flagship policies, such as Zero Carbon Homes and the Green Deal, has resulted in a considerable policy vacuum. This policy gap is likely to exceed 20 $MtCO_2$ within the next decade and must be urgently addressed (CCC, 2015b). Even in long sighted projects, such as the GCB Routemap, there has been a conspicuous absence of long term policy recommendations addressing embodied carbon beyond 2020.

The introduction of policy addressing embodied carbon offers an opportunity to reduce this gap by promoting a broader range of mitigation options, highlighted in Chapter 4. Given the deep uncertainty in the required levels of carbon reduction, and the potential contributions from electricity decarbonisation, CCS and changes in material production, it is imperative that any proposals for embodied carbon policy are situated within an adaptive framework which exhibits a greater resilience to changes in the operating environment. This framework must also be able to identify short-term changes that are consistent with the desired long term system reconfiguration implied by ambitious targets. This chapter considers how developing such a framework through a participatory approach could provide greater resilience and restore industry confidence. The approach adopted is a modified form of the Dynamic Adaptive Policy Pathways (DAPP) proposed by Haasnoot et al. (2013).

Section 7.2 begins by briefly reviewing recent evolutions in planning and adaptation scholarship, before introducing the DAPP approach. Section 7.3 outlines the DAPP development process and applications to date. Section 7.4 presents an early attempt to develop a set of pathways through a participatory workshop with industry practitioners. Section 7.5 discusses the challenges encountered in such an approach. Section 7.6 outlines additional research needs alongside a route for further development and application of the DAPP approach. The chapter concludes with a short summary.

7.2 Literature review

The mitigation of carbon emissions and the adaptation of society to a changing climate represents an unprecedented challenge for policy makers and planners. Managing the requisite changes in the face of multiple sources of uncertainty requires novel approaches to policy development and improvement upon orthodox planning strategies. Past approaches to planning have typically comprised of a static optimal plan based upon a 'most likely' future, or a static 'robust' plan deemed acceptable under a variety of plausible futures. Subsequently, as an unpredicted future unfolds and plans prove inadequate, plans and policies are adapted ad hoc. By this means "*policymaking becomes part of the storyline, and thereby an essential component of the total uncertainty*" (Haasnoot et al., 2013). The past decade of strategic planning and adaptation scholarship has seen the development of a range of alternative approaches including assumption-based planning, robust decision-making, adaptation pathways, and adaptive policy-making (Malekpour et al., 2015). Concepts from these fields such as thresholds, tipping and turning points have been increasingly incorporated into considerations of sustainability under climate change (Werners et al., 2013). There has been a simultaneous rise in more participatory and discursive forms of planning, and the planning process has come to be seen as a mediator for achieving a shared vision underpinned by trust and legitimacy (Malekpour et al., 2015). Whether policy development has experienced a similar evolution in stakeholder participation remains a source of much debate.

In an effort to improve upon existing approaches to policy development Haasnoot et al. (2013) propose combining elements of two prominent fields – 'adaptive policymaking' and 'adaptation pathways' – to develop Dynamic Adaptive Policy Pathways (DAPP). DAPP are intended to include a strategic vision of the future, commitments to short-term actions and a framework for guiding future actions, developed through a participatory approach. In essence, they provide a bridge between highly uncertain long-term changes and the short-term decision making horizons of policy makers. Early applications of DAPP have suggested that the method is preferable to alternate approaches as it provides one coherent, transparent process to develop flexible policy supporting a set of stated goals (Van der Hoek et al, 2016). The process can simultaneously identify potential lock-ins, no-regrets and win-win policy options. Furthermore, the periodic updating of policy advocated by the process should incorporate new information as it becomes available, allowing new opportunities to be seized and threats to be spotted early.

In the case of embodied carbon reduction in the construction sector, the goal of carbon reduction is clear but the policy options are disparate and their potential impacts highly uncertain. An approach to policy development that responds to this deep uncertainty, maintains flexibility and considers interactions between a portfolio of policy options is therefore highly desirable. DAPP exhibits these desirable features but has yet to be applied within such a field. For this reason, it represents an intriguing option for consideration.

7.3 Dynamic adaptive policy pathways

The following sections describe the DAPP development process in detail, applications of DAPP to date, and the scope for developing DAPP for the construction sector.

7.3.1 The process of DAPP development

The approach to developing DAPP is summarised in Figure 37. The following is a brief description of the process, further described by Haasnoot et al. (2013).

The first step requires a description of the study area and the major uncertainties. The intention is to develop a definition of success, such as a set of indicators by which performance of actions can be evaluated and the 'sell-by date' of actions determined.

The second step involves using a set of transient scenarios to investigate the relevant uncertainties and their development over time, with a view to identifying potential policy gaps, opportunities and vulnerabilities. In this case, opportunities are defined as "*developments that can help in achieving the objectives*", while vulnerabilities are "*developments that can harm the extent to which the objectives can be achieved*".

The third step is to compile a list of actions that handle the identified vulnerabilities and opportunities and meet the definition of success.

The fourth step is an evaluation of the actions against the transient scenarios, considering their impact upon the identified opportunities and vulnerabilities.

In the fifth step, a series of logical pathways are assembled into an adaptation map (see Figure 38). Each pathway consists of a concatenation of actions, where a new action is activated once its predecessor is no longer able to meet the definition of success. This adaptation map is analogous to a tube map, wherein terminals

Figure 37: Dynamic Adaptive Policy Pathways development process, based on Haasnoot et al. (2013)

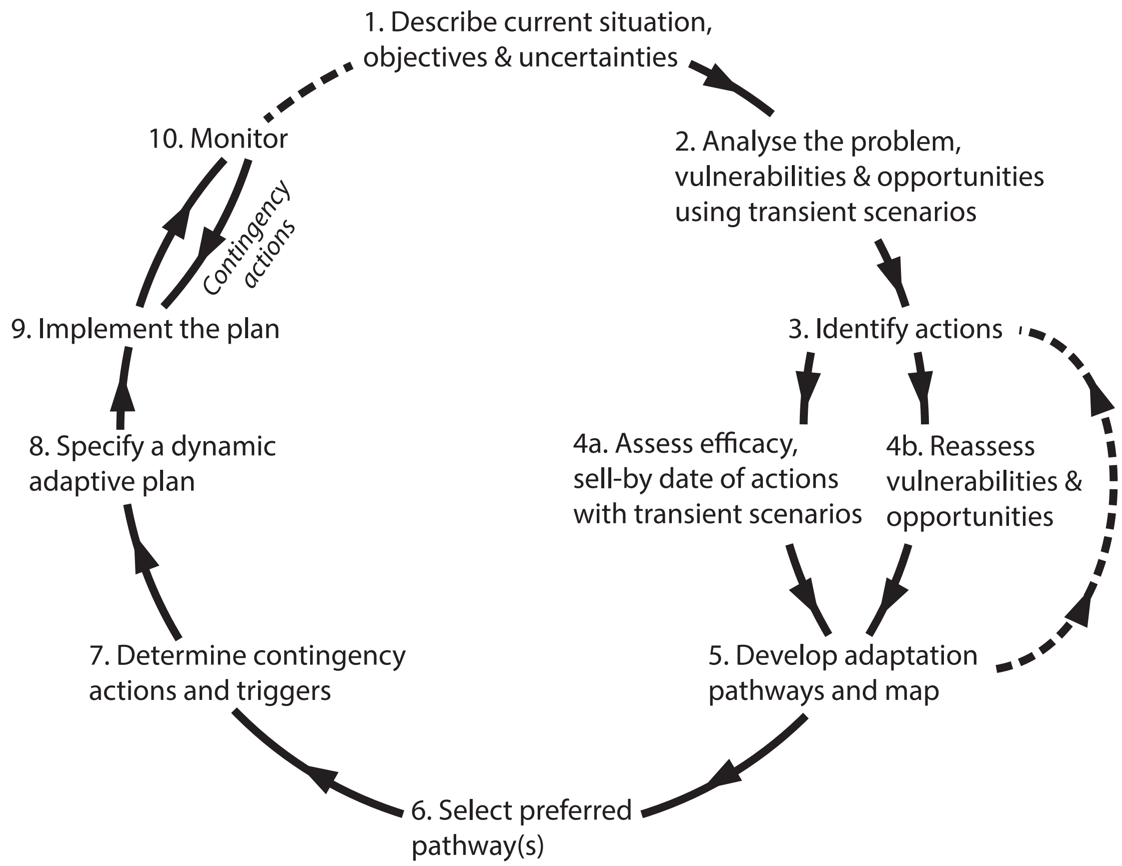
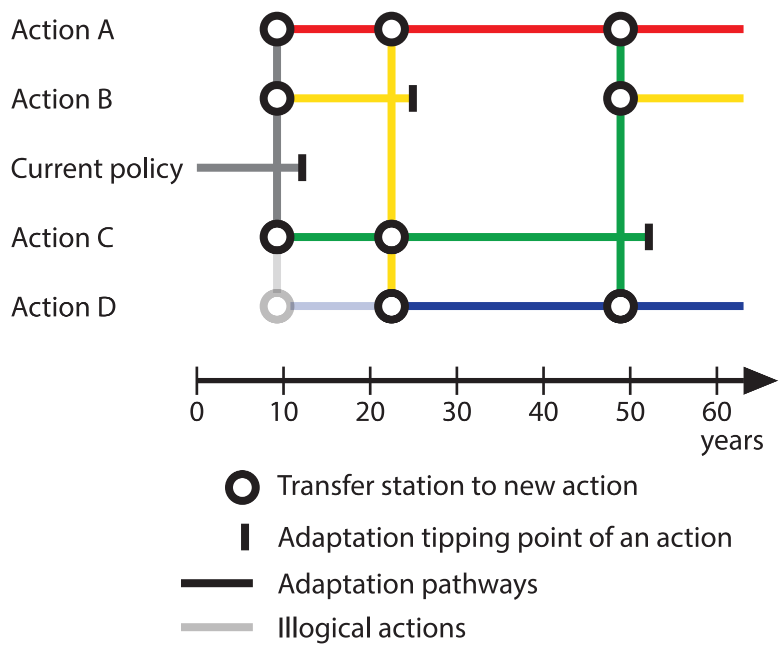


Figure 38: Example adaptation pathways map



represent adaptation tipping points, i.e. the point at which a particular action is no longer adequate for meeting the plan's objectives.

The sixth step requires the selection and detailed consideration of a set of preferred pathways. These pathways will form the basis of a dynamic adaptive plan.

The seventh step establishes a monitoring system and a set of potential corrective, defensive and capitalizing actions that could be taken in response to defined triggers. These triggers represent conditions observed by the monitoring system under which a pre-specified action to change the plan should be taken. Put simply, actions are defined "*to get and keep each of the pathways on track for success*" (Haasnoot et al., 2013).

The later steps formalise the dynamic adaptive plan which specifies what actions should be taken immediately; actions that can be postponed; targets; preferred pathways; and the monitoring system. Initial actions are implemented, progress is monitored and activation of other actions occurs in response to the occurrence of trigger events.

7.3.2 Applications to date

To date, the approach has been applied to a number of case studies, such as Kwakkel et al. (2014) and Hermans et al. (2014) but has received few real world applications. These applications have principally been within the field of water (e.g. Veelen et al., 2015) or waste water (e.g. Van der Hoek et al., 2016) management.

For instance, Veelen et al. (2015) report an application of the approach in planning resilient waterfront developments in Rotterdam. Whilst the approach was deemed "*effective*" in this instance, the authors highlighted a number of perceived weaknesses. The approach is time consuming, requires detailed information and consensus among policy-makers and stakeholders on performance criteria and thresholds. The authors argue that when this information is lacking, the approach may be less useful as a decision support method. However, the authors observed that the method did help planners "*better grasp the timing of adaptation*" allowing them to "*develop a wide portfolio of adaptation actions, which opens up opportunities to couple adaptation with other planned investments*". It also helped to prevent "*possible lock-ins at an early stage in the planning process*".

The core challenge from early applications remains in overcoming the 'curse of dimensionality' whereby the approach becomes excessively complicated or computationally intensive due to the need to consider a multitude of possible futures, transient scenarios, and stakeholder perspectives (Kwakkel et al., 2014). A further challenge lies in establishing appropriate monitoring systems which may necessitate collaborative commitments between stakeholders (Hermans et al., 2014).

In spite of these challenges, the approach offers the opportunity to connect short-term actions with broader systemic changes; provide flexibility in the face of deep uncertainty; and engender a common understanding amongst stakeholders through the collaborative approach to pathway development.

7.3.3 Application to construction policy on climate mitigation

Before considering the application of such an approach to the development of new policy, it is worthwhile briefly considering the past decade of such policy through a DAPP frame. Within this frame, it could be argued that construction policy of the past decade has largely progressed down a series of linear pathways that reached terminals prompted by changes in Government and financial circumstances. In the absence of alternative policies to transfer to, construction policy has developed a stop-start quality, resulting in a lack of business certainty and the rise and fall of numerous cottage industries facilitating key policies. For example, firms providing solid wall insulation, Green Deal assessments and installation of microgeneration technologies. The stop-start approach has also resulted in orphaned expertise and organisations, such as the Zero Carbon Hub. The lack of stakeholder engagement in decisions to revoke key policies, such as Zero Carbon Homes and Feed-in Tariffs, has undermined industry trust and investment (UKGBC, 2015c). Meanwhile, the lack of preconceived contingency actions has resulted in a failure to achieve sustained carbon reductions.

The achievement of strategic carbon reduction targets necessitates that a series of short term actions be taken that engender long term systemic change. These actions must be supported across the supply chain if they are to be effective and prevent professions working at cross purposes, in the manner described in Chapter 5. The active involvement of industry stakeholders in the policy development process is also critical in restoring trust. In these respects, it would appear that a policy development process similar to DAPP could be beneficial for the construction sector. Embodied carbon in particular represents an intriguing testing ground for this approach owing to the lack of existing policy in this area, and the multiple sources of uncertainty described in Chapter 6.

7.4 Developing pathways for the construction sector

The following sections present an initial application of the DAPP approach to embodied carbon emissions in construction. As the approach has received few real world applications, and none within this context, the intention is to test the viability and value of the approach in practice. The intention is not to generate a fully-fledged dynamic adaptive plan, and the process proposed by Haasnoot et al. (2013) is not strictly adhered to. The project is ongoing, and the work reported in the following sections considers the early steps in the pathway development process (steps 1-5 in Figure 37). This includes development of an initial set of pathways. The intention is to validate these pathways through a further stakeholder workshop, which will also incorporate discussion of preferred pathways (step 6). Steps 7-10 including the determination of contingency actions, triggers and monitoring regimes depend upon the particular characteristics of a preferred pathway and are outwith the scope of this thesis.

The following section sets out the research objectives and the methodology adopted for pathway development. This is followed by results from a practitioner workshop, the preliminary pathways and a discussion of the merits of such an approach in achieving substantial carbon reductions.

7.4.1 Research methodology, objectives and boundaries

This chapter has two principal objectives. First, to identify a range of possible policy responses and industry-led actions that could motivate substantial embodied carbon reduction. Secondly, to consider how these actions could be sequenced within a broader network of policy pathways.

The boundaries considered for all possible actions and policies are the full supply chain emissions associated with UK construction activity.

A preliminary set of policies and pathways were developed through an ongoing participatory approach. An initial workshop was hosted at the Royal Academy of Engineering on 11th September 2015, featuring 10 experienced practitioners from leading organisations across the industry supply chain. This small focus group format was preferred to other qualitative approaches, such as individual interviews and questionnaires, as it encourages interaction and discussion between stakeholders with different interests. This allows participants to directly compare experiences and views, and highlights points of agreement and disagreement. This approach is commonly used across a range of disciplines, often in combination with other methods (Morgan, 1996). Workshop participants were selected to provide a breadth of opinion and experiences. The shortlist of invitees included individuals with known experience in embodied carbon mitigation from leading firms across each area of the construction supply chain. The final group of attendees included at least one representative from product manufacturers, contractors, architecture and engineering consultancies, sustainability consultancies, research organisations and the civil service.

The workshop consisted of two sessions, the first reviewing an initial list of policy options and industry-led actions developed by the author in collaboration with Dr. Katy Roelich. This initial list composed of numerous ideas proposed within recent industry reports and debates. Participants were asked to discuss the validity of the options and add additional policies or industry-led actions that were absent from the initial list. The second workshop session introduced participants to the pathways approach, described in Section 7.3, and asked participants to consider the potential sequencing of policies and actions, as well as the feasibility and adaptability of each policy option. To facilitate this process the policies and actions were displayed on a range of colour coded cards that could be annotated and placed in sequence. Discussions surrounding the policies were captured by a scribe with contributions subject to the Chatham House Rule. The workshop was followed by a broader program of stakeholder engagement including individual meetings with additional stakeholders.

The following sections briefly cover the initial steps of the DAPP process and results from the workshop.

7.4.2 Describing the current situation and analysing the problem

In large part the previous chapters (Chapters 1 and 2 in particular) and the Low Carbon Routemap for the Built Environment (GCB, 2013b) describe the current situation and principal sources of uncertainty. Chapter 6 also included modelling of a range of transient scenarios that provide a baseline for analysis. The remaining elements of steps 1 & 2 (see Figure 37) of DAPP development are: to set an objective and define success; suggest an appropriate set of indicators by which performance of actions can be evaluated; and to identify potential vulnerabilities and opportunities.

The objectives defined in Construction 2025, principally the achievement of a 50% reduction in carbon emissions from the built environment by 2025, and the longer term ambitions set out in the GCB Routemap are deemed to be the policy objectives in this instance. Success constitutes achieving these objectives whilst meeting the building and infrastructure needs of the UK population. The high-level indicators of progress are the sector annual carbon emissions from both territorial and consumption-based accounting perspectives. Measures of carbon intensity for different project types should constitute a lower tier of indicators.

There are numerous opportunities presented by plausible future developments. For example, the recent adoption of a global mitigation agreement could motivate reduced carbon intensity of foreign suppliers and cultivate an export market for low carbon construction products. Likewise there are many potential vulnerabilities. For example, the existence of some domestic material producers is threatened by fierce international competition, such as alleged steel dumping. The well-publicised shortage of skills within the UK construction sector also threatens to limit the roll out of low carbon designs. Given the scope of the project, a full list of opportunities and vulnerabilities is not presented at this stage. The following section addresses step 3 by identifying a range of actions that could support embodied carbon reduction.

7.4.3 Government policies and industry-led actions that could support embodied carbon reduction

Past reports including the GCB Routemap (GCB, 2013b) and the Infrastructure Carbon Review (HM Treasury, 2013) have identified a range of low carbon activities that must be undertaken. A number of industry events – such as the ASBP 'Embodied Carbon: Why, how and when? Debate', and the UKGBC's 'Embodied Carbon Action and Implementation' conference – have featured discussion of policies that could create a supportive environment for these activities. The Embodied Carbon Task Force report also included some suggestions extending beyond the inclusion of embodied carbon as an Allowable Solution under the Zero Carbon building regulations (Battle, 2014). From these sources and the author's experience an initial list of policy options and industry-led actions was developed. The initial list was

Table 22: Policies and actions that could support embodied carbon reduction

PRODUCTS
Develop common UK National Embodied Carbon Database from mix of EPDs and generic LCA data
Require production of EPD to support environmental claims of manufacturers
Legislate to make production of EPDs mandatory
Legislate to achieve minimum EPD standards with penalty for exceedance/incentive for going under
Develop certification systems for alternative materials
Provide guidance and training in use of alternative materials
Promotion and advocacy for alternative materials
Mandatory labelling of products that have potential for reuse
Develop database of materials in use that are suitable for reuse at end of life
PUBLIC PROCUREMENT AND REGULATED SECTORS
Develop approach for performance-based specification across all sectors and construction types
Enhance the Green Public Procurement criteria for construction
Mandatory measurement and reporting of capital carbon on public and regulated sector construction
Improve guidance on capital carbon in Green Book and Magenta Book and increase from optional to mandatory consideration in project evaluation
Include explicit calculation and reporting of capital carbon in National Infrastructure Plan
GENERAL PROCUREMENT
Extend WRAP's work on Carbon Efficient Procurement to reflect best practice and upgrade embodied carbon to standard rather than optional element
Promote Carbon Efficient Procurement guides
Extend GHG reporting requirements for quoted companies to include embodied carbon in new buildings in addition to current operational emissions
DESIGN
Establish voluntary commitment for large contractors to add embodied emissions data to WRAP Embodied Carbon Database
Introduce mandatory requirement for public sector projects to assess embodied carbon and report data to WRAP Embodied Carbon Database
Introduce planning requirement to report capital carbon
Introduce planning requirement to report measures to design for deconstruction
Legislate to achieve minimum capital carbon standards against established benchmarks with penalty for exceedance/incentive for going under
Enhance BIM requirements to include material quantities and embodied carbon data

reviewed and extended through the first session of the practitioner workshop. Table 22 contains the resultant list of potential policies and actions. These options are broadly grouped by the supply chain area they would principally affect.

7.4.4 Developing pathways for embodied emissions policy

The second workshop session asked participants to consider the potential sequencing of actions, alongside the feasibility and adaptability of each action. The discussions spanned the particulars of specific actions, broader critiques of the methodology, and highlighted deeper challenges preventing feasible policy development. The following sections consider the principal issues using comments from the workshop participants and additional analysis from the author.

7.4.4.1 Narratives and framing of policies

In order to achieve political support, any policy must be framed to appear compatible with the prevalent political narrative of the day. It remains unclear how action on embodied carbon can be convincingly framed to fit within the broader strategic narrative of the current Conservative Government, characterised by one workshop participant as "*more jobs, less cost*". The core narrative of the ICR was that "*reducing carbon reduces costs*" (HM Treasury, 2013 p. 3) but, without a robust evidence base, many in the industry remain sceptical. Such an evidence base is unlikely to be developed without the introduction of additional drivers. In the absence of a broader strategic narrative for climate change in the UK, it is impossible to appeal to the benefits of action addressing embodied carbon purely in terms of climate mitigation (Bushell et al., 2015). In order to secure engagement from a multitude of actors across the complex industry supply chain, it may be necessary to simultaneously appeal to numerous co-benefits or to a broader narrative of improved competitiveness.

Participants argued that one potential narrative could be marketing the UK construction industry – and product manufacturers in particular – as lower carbon than their international competitors. However, for such a claim to be of value it would require a significant increase in client demand for low carbon products and designs. Translating growing international climate mitigation efforts into demand for low carbon building products may take some time and the greater profusion of regulation, or at least awareness, of embodied carbon. Should demand increase there is also scope for skills in embodied carbon assessment and low carbon design to be marketed overseas. It could be argued that such a strategy would drive domestic job creation whilst reducing project costs and contributing to the Construction 2025 objectives. It remains to be seen whether such a narrative could prove compelling.

The workshop discussion highlighted a serious weakness of the DAPP development approach in this respect. The approach does not contain any explicit consideration of narratives and framing in the early stages, only implicitly during the later pathway selection. Thus there is a risk of developing initial pathways wherein each strand is not necessarily compatible with an overarching narrative. A resilient policy must appeal either to a universally acceptable narrative, or be sufficiently malleable to allow reframing for multiple narratives. This will usually require explicit consideration and appeals to co-benefits, which are not considered in the early stages of the DAPP approach. However, the participatory approach inherent to pathway development could easily be adapted to include collective narrative-forming and facilitate the sounding out of proposed narratives at the early development stages.

7.4.4.2 Gathering evidence

Despite growing industry interest and expertise, the evidence base that could inform policy making remains limited. The majority of embodied carbon assessment and mitigation to date has been undertaken by a small number of exemplar firms: 'the usual suspects' (UKGBC, 2015a p. 12). Many within the industry remain sceptical that the demonstrated cost and carbon savings on these projects can be replicated at scale outwith this group of innovative firms. The aggregate number of assessments remains insufficient to form detailed benchmarks, and there is no central depository for information on costs incurred. Consequently, there is insufficient evidence to undertake the sort of economic analysis required under a typical policy impact assessment. Encouraging sufficient carbon assessments to form a robust evidence base will likely require additional stimuli. However, additional stimuli are unlikely to be introduced without a robust evidence base. Overcoming this catch 22, in an environment where funding for exemplar projects is limited, will likely require leadership from industry firms and institutions alongside support from the research community. This will require extensive collaboration and a willingness to share data and experiences.

If the strategic political narrative does change, it is imperative that an evidence base is already in place that can support appeals to the new narrative. Effectively capitalising on changes in narrative requires a prolonged accrual of evidence, rather than a frenetic response to opportunities presented by consultations and the like. Even after initial stimuli are secured, or early actions and policies adopted, the continued development of an evidence base remains fundamental to the progression along any policy pathway. The DAPP approach should be adapted to include explicit consideration of how development of this evidence base will be supported along each pathway. This should complement the consideration of any monitoring regime.

7.4.4.3 Policy and action ownership

The workshop discussion also highlighted the lack of obvious owners for policies and actions. No Government department has sole ownership of this issue.

Whilst DECC notionally formulates plans for climate mitigation, policies affecting new build are principally set by DCLG and local authorities. Meanwhile numerous other departments, such as the Department for Transport and DEFRA, determine the overall demand for new building and infrastructure stock through their investment decisions. In addition to the lack of cross-departmental strategy and collaboration, even within departments it is difficult to identify individuals whose remit could sensibly include embodied carbon. Consequently, for advocates within the industry lobbying for action it is difficult to distinguish appropriate points of influence. Embodied carbon has yet to garner serious consideration within mainstream policy circles and, in many ways, remains an issue without a home.

Similarly, within the industry there are few suitable organisations who can take effective ownership of this issue. Many of the proposed actions, such as establishing and maintaining a common UK LCI and EPD database, require investment and long term commitments to maintenance from an impartial and respected source. This source must be willing to demonstrate leadership and be seen to represent firms spanning the full supply chain. Recent movements from professional institutions such as the RICS, and member organisations such as the UKGBC, have reflected a growing industry interest but there remain few commercial advantages to demonstrating leadership on this issue at the present time. If the desired actions are to be undertaken, it will require not just leadership from a handful of high profile firms but sustained support from a cross industry group.

7.4.4.4 Policy and action sequencing

Workshop participants' attempts to sequence the suggested policies and actions highlighted a number of chicken and egg problems. Certain actions clearly reinforced other actions but the discussion highlighted the difficulty in determining an appropriate first step.

On the whole, participants felt that drivers providing a market 'pull' must be implemented prior to any providing a 'push' on the supply chain. The 'pull' drivers must focus on stimulating client demand for low carbon structures, as this would allow sympathetic actors within the supply chain to justify necessary investments in skills and technology change. Client demand was also seen to align the supply chain and provide the most effective means of ensuring professions work to the same ends, as highlighted in Chapter 4. The general sentiment within the workshop was that changes in public procurement represented the best opportunity to stimulate demand in the near term.

Once such drivers are in place, they can be reinforced by 'push' drivers focussing upon the product supply chain. These would include actions such as promoting or requiring production of EPDs. Participants believed such actions or policies could potentially be rolled out in tandem with increased BIM requirements, encouraging the use of common LCA data within building models.

7.4.4.5 Identifying advocates

The adoption of any individual policy or action must be supported by advocates within the industry. Identifying potential advocates for each policy and the transition between policies is arguably as important as identifying owners for implementation. It takes time for advocates to establish relations and influence across industry and within government, and to develop the necessary social and political capital to effectively support a transition. In this sense the advocates must be primed ahead of key decision making points. Development of pathways should therefore incorporate some consideration of potential advocates and the accrual of social and political capital that must occur in tandem with any evidence gathering.

The current crop of advocates for action on embodied carbon is largely restricted to individuals within a handful of firms and small membership organisations supporting low carbon products (such as the ASBP). High profile institutional advocates representing firms across the supply chain will be required if the adoption of more stringent measures is to be successful. Therefore current advocates must focus on developing support within these institutions as well as connections within key government departments.

7.4.4.6 Establishing a common boundary

In order to appeal to the industry, policy must be carefully crafted to ensure that it does not explicitly back any particular material and therefore must directly address a common metric, such as carbon. However, given the degree of subjectivity and variation in accounting methods – as discussed in Chapter 2 – proponents of regulation often argue that it is imperative that any policy must stipulate an agreed accounting approach. Recurrent disputes between major material producers around the inclusion of carbon sequestration in natural materials, post-life recarbonation of concrete, and recycling and reuse assumptions for metals, often hijack debates on regulation of embodied carbon and reflect the reality that establishing consensus boundaries may prove difficult. There will always be a degree of subjectivity in LCA, as certain assumptions must be made, or scenarios formed, to assess unpredictable future outcomes. Some decisions must be left to the discretion of the practitioner conducting the carbon assessment. There is a legitimate risk that assessors may simply select boundaries that yield the most favourable results for current practice and real carbon savings achieved will be minimal. However, this concern should not prevent greater measurement or justify wholesale inaction. Even without resolving these issues, policies such as mandating the measurement and reporting of embodied carbon to BS 15978 could improve awareness and engender the desired change in industry mind-set. Encouraging practitioners to measure even a common subset of the full impacts could stimulate incremental improvements in design, generate increased client interest and motivate evaluation of product carbon data. In short, ongoing debates around boundary assumptions must not restrict the practice of carbon assessment.

7.4.4.7 Other observations from workshop participants

Participants believed that the principal challenge is stimulating client interest and overcoming an unwillingness to invest additional fees in embodied carbon assessment in spite of potential cost savings. Participants stressed that to overcome this aversion it was imperative that incentives be introduced to encourage greater client consideration of Scope 3 emissions. Suggestions varied between mandating reporting for large firms through to potential tax breaks based on reductions against a baseline.

Participants also expressed concern that the rise of non-EU imports represents a serious competitiveness issue and that without the introduction of a border carbon tax or similar instrument, domestic manufacturers would not benefit from producing lower carbon products. Furthermore, some participants expressed a concern that too narrow a focus on carbon – rather than resource use more generally – risked promoting a relocation of material production to countries with low carbon electricity sources (e.g. France).

Some participants believed it is important to start with organisational level carbon schemes that encourage individual firms to develop their own targets and business case before broader policy is introduced. Several workshop participants also stressed that any policy response addressing embodied carbon must also provide strong incentives for prolonged use of existing buildings.

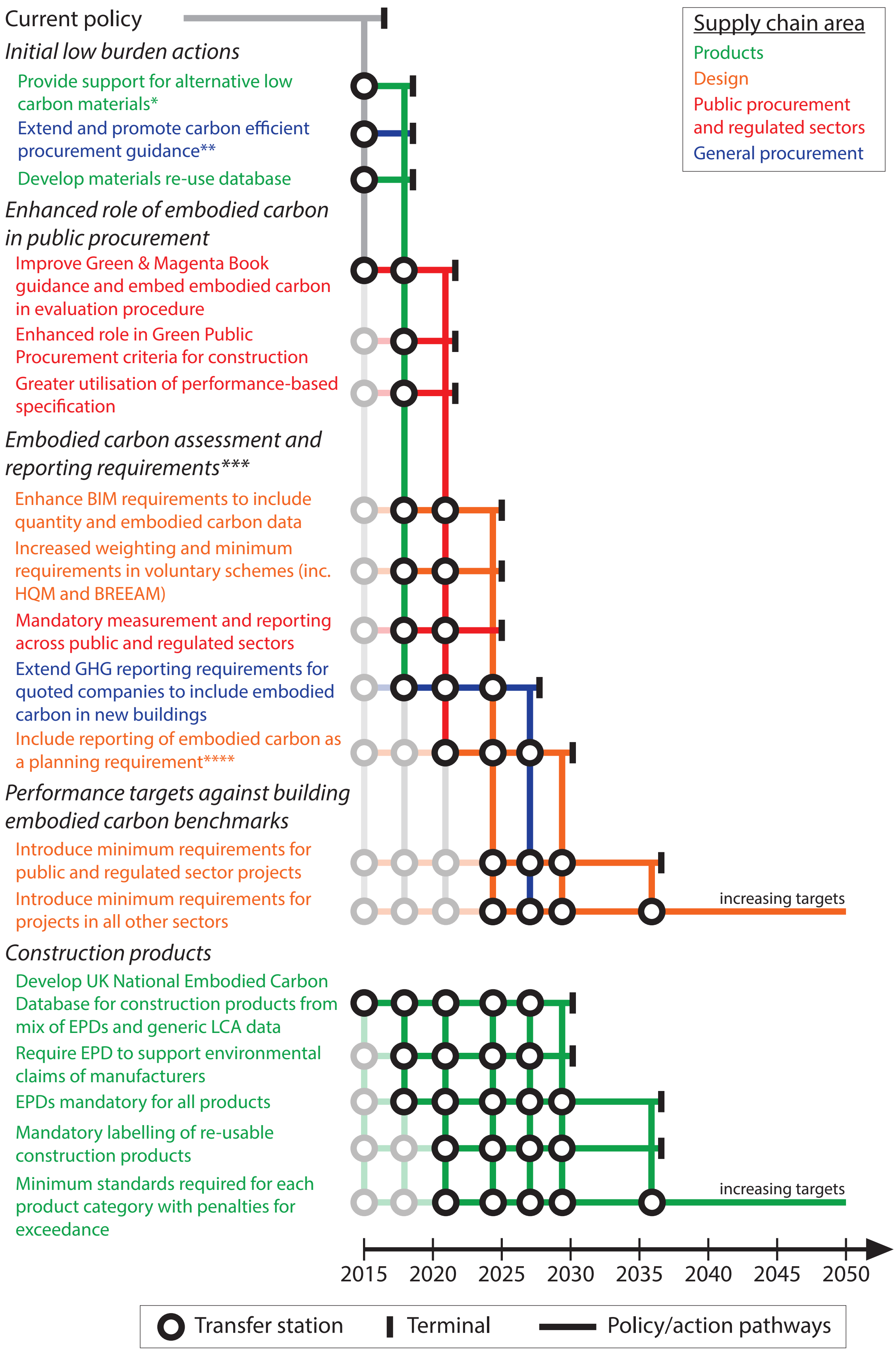
One participant expressed a view that the recent levelling-off of the National Planning Policy Framework restricted the ability for Local Authorities to specify above regulated standards or to encourage the use of innovative materials and practices. An idea was also put forward that the Public Services (Social Value) Act could perhaps serve as alternate grounds for justifying enhanced requirements.

7.4.4.8 A preliminary set of pathways

Drawing upon the views expressed by workshop participants and their attempts at action and policy sequencing, the author developed an initial pathways map (see Figure 39 overleaf). This map is intended as a starting point for further debate and has not been subject to detailed quantitative assessment. It is presented here to indicate some potential forms and timelines that a credible forward plan for embodied carbon in construction might take.

The terminals represent moments at which prior actions are projected to prove inadequate at meeting carbon reduction targets. These terminals have been approximated based upon the analysis in Chapter 6 which demonstrated that under all scenarios for population growth, economic growth and infrastructure development, current actions on embodied carbon will likely prove insufficient to

Figure 39: Preliminary pathways



* Including development of certification systems, provision of guidance and training

** Update WRAP guides to represent best practice and ensure broader distribution

*** All data uploaded to WRAP Embodied Carbon Database facilitating benchmarking

**** Evidence gathered from leading LAs can support implementation of a national approach meet interim targets beyond the early 2020s, with deep reductions required in later decades. Policies and actions that only affect public procurement and regulated sector emissions are likely to impact on around a third of total sector emissions. Consequently deep reductions in later years will necessitate additional action across all types of construction.

The map highlights that if embodied carbon in construction is to contribute significantly to UK carbon reduction targets, the groundwork must be laid in the next decade to ensure sufficient data to support regulation that could drive substantive carbon reduction in the longer term. The earlier measures are adopted that generate client demand for embodied carbon assessment and support the production of benchmark data, the earlier regulated targets can be introduced and the greater aggregate emission reductions can be achieved. Given the lead times for these policies, significant reductions are unlikely to affect sector total emissions until the 5th Carbon Budget and beyond.

All early measures must contribute to development of the benchmark data that will serve as the ultimate driver of deeper reductions in the long term. Measures targeting product manufacturers and measures focussed on procurement and design must be developed in tandem to support this data gathering. It is likely that leadership will be required from local authorities and best practice stimulated by changes in public procurement. This will require buy in from a broader stakeholder group than is currently present within the embodied carbon community.

In addition to the suggested actions and policies, efforts should be made to continue decarbonisation of all construction product supply chains. Similarly, best design practice should be shared and further investment in training and skills development will be required. The production of simplified calculation tools suitable for use by smaller firms will also be essential.

Potential European policy interventions have not been included in the preliminary pathways. However, with common resource efficiency benchmarks slated for introduction in 2017 and further interventions a likely feature of the upcoming circular economy package, intervention in some form is probable.

7.5 Discussion

The initial stakeholder workshop highlighted a number of weaknesses in the DAPP methodology. These included the lack of explicit consideration of narratives within early stages of pathway development; insufficient consideration of policy and action ownership as the method implicitly assumes one central decision maker; and insufficient consideration of how evidence gathering and the development of social and political capital must be supported throughout pathway progression. In spite of these weaknesses, the methodology provided a good frame for engaging stakeholders in discussion and helped instil the need to consider policy sequencing with due regard for feasibility, flexibility and allocation of responsibility.

Stimulating a staged multi-actor response to embodied carbon will prove challenging, particularly without clear ownership of the issue within industry or Government. Given the range of competing interests, multiple sources of influence and legitimate methodological disagreements, it may prove difficult to achieve a consensus view. The problem needs to be reframed for multiple audiences, and must simultaneously appeal to a number of distinct narratives. Handling this process may necessitate a more explicit mapping of stakeholder interests, influence and narratives than is prescribed under the DAPP development process. Further research should undertake this mapping, whilst continuing to consider the details of particular policies, their interactions and potential sequencing. Potential narratives should be explored with policy makers and practitioners, and the development of a corresponding evidence base must be supported by industry institutions and the research community.

Feasible pathways for embodied carbon are likely to feature a multi-level response, with local authorities and a small cohort of firms initially demonstrating best practice, introducing progressively more stringent requirements, assembling an evidence base for policy makers and disseminating their experiences to the mainstream industry. Once a robust evidence base is in place and an appropriate narrative determined, national regulation could proceed through a number of pathways, as indicated in Figure 39. This would likely commence with instruments supporting data gathering or measurement rather than mandating reductions. The precise form of regulation beyond this stage will likely depend upon the scale of carbon reductions required at the time of introduction. This will in turn depend upon the observed rates of new build, supply chain and grid decarbonisation, and the progress made towards commercialisation of CCS. If earlier actions take place over a period of say 5-10 years – during which time adequate benchmark data is gathered – then the required levels of reduction could be tailored to meet interim targets out to 2050, with a corresponding policy pathway selected and more detailed policy proposals prepared.

In the meantime the industry must make progress on evidence gathering and not allow disputes around system boundaries to justify paralysis. Professional institutes and membership organisations, such as the UKGBC, must take ownership and lead on this issue, supporting common data repositories and dissemination of best practice. In the absence of new policy options that appeal to the dominant political narrative, advocates must explore adaptation of existing policies or exploitation of tangential legislation (e.g. the Social Value Act) to encourage initial uptake of embodied carbon assessment. Advocates must also focus on developing relations and influence within key government departments.

Policy makers must begin to engage with this issue and develop an understanding of the terminology, the implications of existing strategic targets and the multiple sources of deep uncertainty described in Chapter 6. There is scope for embodied carbon reduction to make a sizeable contribution towards meeting later UK Carbon Budgets but these reductions will only be achieved if initial supporting actions are taken in the coming decade. This is unlikely to occur without a change in approach to policy development. There is a risk that the politicised nature of construction policy could constrain the willingness of stakeholders to engage in an open participatory approach such as DAPP development. However, the benefits of such an approach are clear. The potential to restore trust; provide clarity by making priorities and narratives explicit; and ensure alignment of objectives across the value chain are obvious advantages over past approaches to policy development. If policy makers are seeking to provide the "*credible, clear and sustained*" policy advocated by the Calcutt Review (Calcutt, 2007 p. 89), then developing long term adaptive pathways in conjunction with stakeholders represents the current best approach.

7.6 Recommendations for further work

The recommendations arising from this work fall into two categories: adaptations to the DAPP process; and next steps in developing embodied carbon policy for the construction industry.

7.6.1 Adaptations to the DAPP process

A clear criticism is that the current DAPP interpretation of deep uncertainty is primarily limited to the numerical uncertainty of physical events, and does not give sufficient attention to other sources of uncertainty surrounding the interaction of stakeholders and the problems introduced by distributed decision-making. Adapting the approach for further applications in climate mitigation will require changes to the process outlined in Figure 37. The following are a series of recommended changes to address the weakness summarised in Figure 40 overleaf. Key adaptations to the process are highlighted in Figure 41.

The initial stage (Step 1 on Figure 41) should include an explicit mapping of stakeholder interests, influence and current narratives. The resultant stakeholder map can then be used to identify suitable owners for actions and policies, potential advocates for policy transitions, and common interests amongst stakeholders. This stakeholder map can then support the development of a range of narratives through subsequent stages (Steps 2-3). Embedding the consideration of alternate narratives within the early stages of the process should encourage debate between stakeholders and improve the chance of developing pathways that meet common or compatible narratives.

Steps 3-5 must include assignment of actions and policies to owners, be they firms, institutions or government departments. When represented in the subsequent pathways map, actions and policies should be clustered by actor. This makes it immediately apparent at what stage buy in from each actor will be required and to what extent progress can be made without buy in from particular actors.

The transfer between any two stations on the pathways map requires advocates and a certain amount of evidence. Identifying potential advocates, and where influence must be further developed, ahead of decision making points should ease transitions. Similarly, identification of likely evidence required for adoption of any given policy or action can allow a corresponding mapping of the evidence gathering process. Understanding how evidence and influence are developed in tandem with other actions and policies within the pathways map is crucial to preventing stop-start policy making. For instance, regulation restricting embodied carbon intensity at a building level would require prior collection of many building level LCAs in order to set appropriate targets. Prior policies or actions to stimulate assessment and submission of LCAs would be required to support this evidence gathering. The adoption of regulation would also require advocates within the industry and within government. The connections and political capital required to support this must be simultaneously fostered during the evidence gathering phase.

Understanding how evidence and influence developed through particular actions and policies can also support further actions from additional actors is crucial in identifying preferable pathways. For instance, measures supporting production of EPDs amongst product manufacturers would support designers in

Figure 40: Outstanding questions in DAPP approach

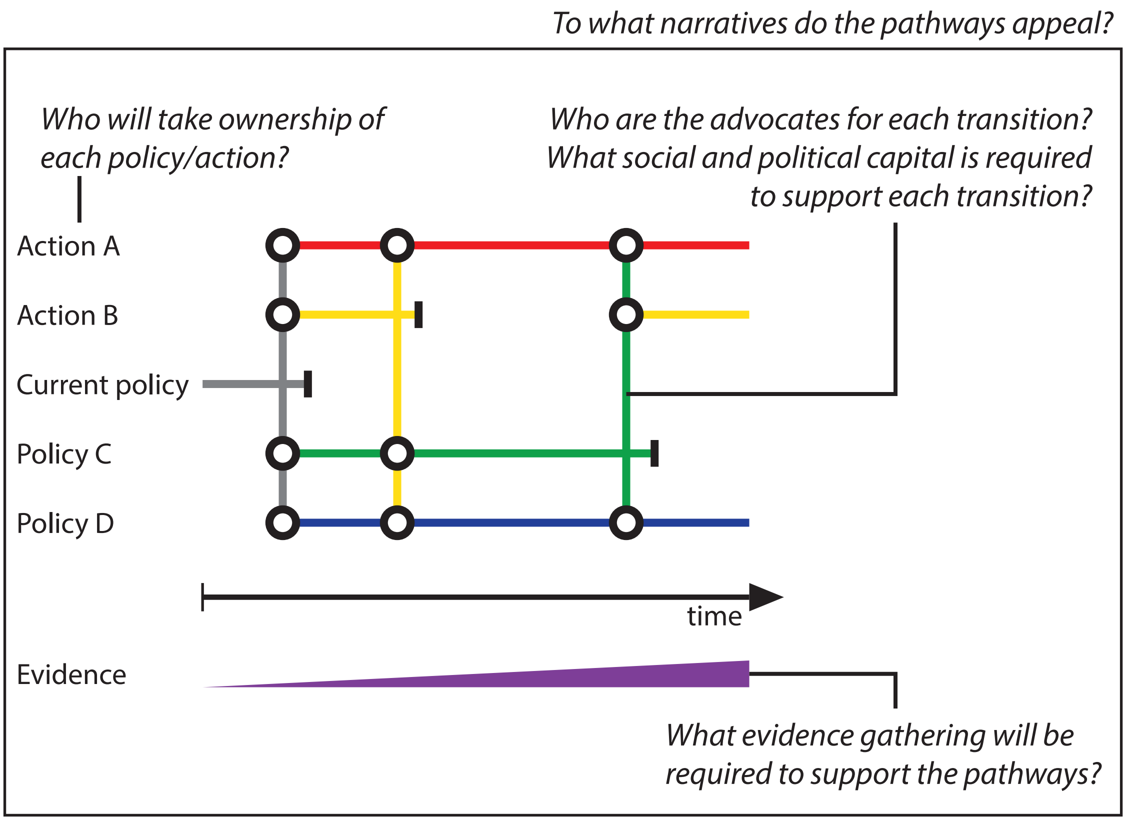
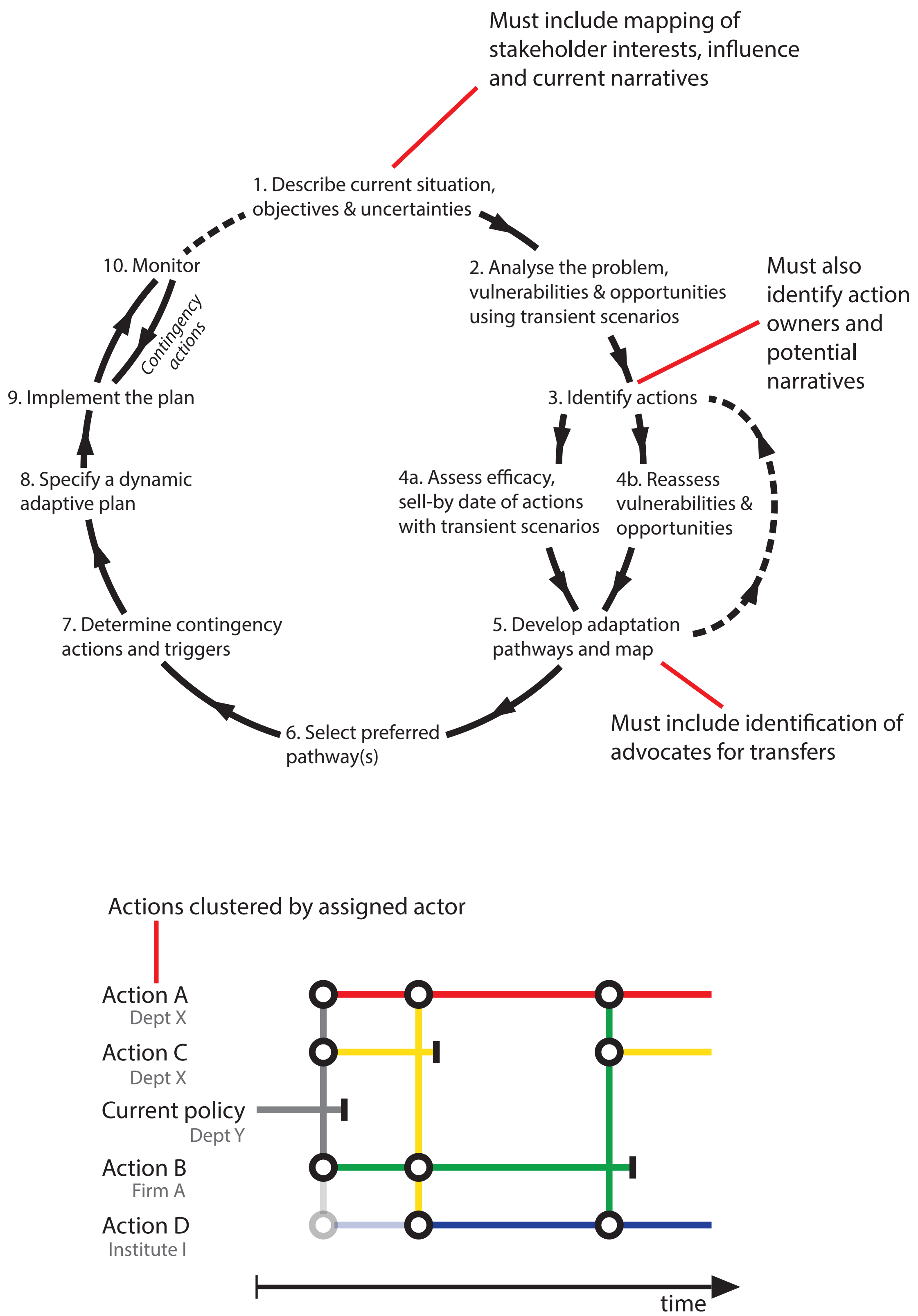


Figure 41: Suggested additions to DAPP development process



completion of building level LCAs, which could in turn provide evidence for policy makers considering regulation of embodied carbon. Understanding how each action reinforces another is therefore also an important part of Steps 3-5.

In summary, the process must be adapted to include: explicit mapping of stakeholder interests and influence; consideration of narratives throughout the process; clearly assigned ownership of policies and actions; identification of potential advocates for transitions; and specific consideration of evidence collection and the development of social and political capital.

7.6.2 Next steps in developing embodied carbon policy for construction

The workshop described in Section 7.4 was a first step in developing appropriate pathways for the construction industry and forms part of a continued and broader program of stakeholder engagement. Further activities and discussions will include: mapping of stakeholder interests and influence; development of more detailed policy proposals; and a second stakeholder workshop. This second workshop will likely take the form of encouraging a broader array of stakeholders to interact with a set of potential pathways, making and debating adjustments, and discussing corresponding narratives. More work must also be done to investigate the scope for adapting existing policies to incorporate embodied emissions.

In addition to development of policy proposals and pathways, greater granularity and sophistication of the supporting models will be required to accurately assess the potential impacts of each action. This will require further data gathering from the industry, and likely exploitation of new sources of information, such as BCIS submissions. It will also require further disaggregation of the UK BIEC model and integration with economic models to support full policy impact assessment.

If current advocates for action on embodied carbon are to gain traction, they must garner greater support from cross-industry institutions (such as the UKGBC) and develop the evidence base for cost savings, product and building level carbon data. Significant time and resources were committed to lobbying for the inclusion of embodied carbon as an Allowable Solution, ultimately to no end. However, the commitments made to data submission throughout this process should be honoured and could support future action. Advocates must not be disheartened by apparent disinterest from national policy makers and should pursue opportunities presented at a local and European level. Ongoing EC consultations may well shape embodied carbon policy in the long term. Meanwhile, leading local authorities can strengthen requirements in the short term by spreading best practice. This in turn can support the development of an evidence base. However, given their limited resources, sharing of local authority experiences may need to be facilitated by a third party.

7.7 Summary

The past decade of regulation supporting carbon reduction in the built environment has been adopted in a piecemeal fashion resulting in minimal emission reductions. Headline policies have been subject to repeated and often sudden revision, creating precarious cottage industries, orphaned expertise and organisations, and undermining industry trust and investment. The current policy vacuum presents the opportunity to adopt a new approach. Any alternative approach must exhibit greater resilience to changes in personnel and the operating environment and align interests along the supply chain.

One such alternative is the development of dynamic adaptive policy pathways through a participatory approach. The pathways developed through such an approach retain the flexibility to respond to changing circumstances, technologies and ambitions whilst highlighting critical short term actions and key decision making points for policy makers. This chapter presented a first attempt at applying this approach to a new policy area within the field of climate mitigation. This included the identification of a range of policy responses and industry-led actions that could motivate substantial embodied carbon reduction, and a first attempt to combine them into a broader network of policy pathways.

Weaknesses in the DAPP approach were highlighted through a stakeholder workshop, and subsequent recommendations outline how the approach could be adapted and improved for application in other areas of climate mitigation. The pathways proposed in this chapter represent a first step in developing a coherent long term strategy for embodied carbon in construction. In spite of the limitations identified, the DAPP approach and the inherent process of stakeholder engagement represents a promising alternative to past policy making in this area. The broader adoption of such a forward-looking approach could foster an environment which enables long term business decision making; restores industry trust through open participation; and incorporates interests of all supply chain members. Achieving these three aims will be crucial in developing an adaptive long term policy framework that can meet sector carbon reduction targets in the face of deep uncertainty.

8. Conclusions and recommendations

> *In literature and in life we ultimately pursue, not conclusions, but beginnings.*
>
> Sam Tanenhaus

8.1 Introduction

The overarching aim of the research presented in this thesis was to understand what role embodied carbon abatement could play in meeting the UK's medium-term sectoral and long term national carbon reduction targets. The combination of quantitative and qualitative work presented in the preceding chapters depicts the range of measures that could reduce embodied carbon and the sizeable contribution they could make towards meeting the goals of Construction 2025 and later UK Carbon Budgets.

Successive chapters introduced: a novel evaluation of the embodied carbon emissions associated with the UK construction sector supply chain; a review of alternative materials, technologies and practices; qualitative research identifying barriers to adoption of low carbon building materials; a novel model, UK BIEC, for translating sector emission reduction targets into project level targets; a scenario analysis of future embodied carbon emissions; and a range of possible policy responses positioned within a series of pathways developed through a participatory approach. In aggregate these contributions go some way towards depicting the desirable features of a robust plan addressing embodied carbon. This chapter summarises those contributions and sets out additional areas requiring further research.

The following section briefly summarises the novel contributions of this thesis. Section 8.3 further describes the work completed and the principal conclusions of each chapter with reference to the project research aims. Section 8.4 reviews the limitations of the research, whilst Section 8.5 offers some remarks and resulting recommendations. Section 8.6 suggests a number of avenues for future work. Section 8.7 contains concluding comments.

8.2 Novel contributions

This thesis makes four principal contributions to the growing literature on climate change mitigation within the built environment.

First, it contains the best estimate to date of the embodied carbon associated with the UK construction supply chain. This provides a credible alternative to the figure published in the influential Innovation and Growth Team report (HM Government, 2010) often cited by practitioners, policy-makers and researchers. For the first time, analysis of the spatial origins of these emissions validates the hypothesis that policies directed solely at UK or EU material producers are unlikely to achieve sufficient reductions in embodied emissions to achieve sector targets.

Secondly, the thesis provides a comprehensive presentation of the barriers to adoption of low carbon materials based upon a systematic review of the literature, a practitioner survey and a series of detailed interviews with industry leaders. The analysis highlights barriers that are common across materials and the common intervention points that could support a range of low carbon solutions. The subsequent discussion also offers novel insight into the policies and practices that could support greater adoption.

Thirdly, the thesis introduces a novel framework for linking sector carbon reduction targets with project carbon intensity targets used by design teams. The framework forms the basis of a new UK Buildings and Infrastructure Embodied Carbon model (UK BIEC) that integrates output from a multi-regional input output model with a database of building life cycle assessments. This integration of top-down and bottom-up data sets represents a novel approach within this field. The corresponding scenario analysis highlights the influence of external factors (such as demand for new building stock) on the likely project emission reduction targets. The author also demonstrates how proposed future iterations of the model could support decision makers by facilitating quantitative analysis of changes in building design and regulation.

Fourthly, the thesis presents a range of policy responses and industry-led actions to motivate embodied carbon reduction in a series of dynamic adaptive policy pathways (DAPP) developed through a participatory approach with key stakeholders. These pathways represent the first application of this state-of-the-art planning approach within this field. The initial pathways provide a first glimpse of how a suitable package of policies could be assembled and sequenced to promote embodied carbon mitigation. The subsequent discussion also proposed numerous methodological improvements to the DAPP development approach.

8.3 Summary of research conclusions

The project research aims detailed in Section 1.6 are summarised in Table 2 on page 26. The following pages address each of these aims in turn, summarising the work completed and any conclusions arising from the research.

Research aim 1

Conduct a robust evaluation of the embodied carbon emissions associated with the UK construction sector supply chain

This research aim was addressed using a combination of MRIO analysis and outputs from the UK BIEC model. This included computing the distribution of emissions by location, intermediate product and final product. The following conclusions were drawn.

Aggregate embodied carbon emissions from UK construction are sizeable

The time series presented in Figure 42 overleaf shows that aggregate embodied carbon emissions from construction are already comparable with tailpipe emissions from all cars on UK roads. Over the past decade the overall trend in emissions has largely followed trends in total construction activity and is set to increase with growing investment in housing and infrastructure.

Targeted emission reductions will require interventions across all building typologies and supply chains

Impacts are broadly distributed across supply chains and structure types, as illustrated in Figure 43 overleaf. Interventions that solely target one element of this graphic will prove insufficient in achieving reductions of the magnitude recommended in the GCB Routemap. For instance, interventions solely targeting UK material manufacturers, or addressing a specific segment of output such as housing, will prove inadequate. This challenges a common misperception within the industry that embodied carbon is predominantly a concern for infrastructure projects and will primarily be solved through improvements in key material production processes. Meeting reduction targets will require interventions that promote both improvements from material producers and reductions in total material demand. This may necessitate uptake of embodied carbon assessment in industry segments where it is currently less common and require material producers to adopt alternate business models that support reduced throughput of material.

Research aim 2

Use the existing literature to appraise options that could deliver substantial reductions in the use of construction materials with carbon-intensive supply chains

This research aim was addressed by conducting an extensive literature review of alternative building materials, design strategies and business models. The following conclusion was drawn.

A multitude of alternative materials, design strategies and business models will be required to deliver reductions in the use of carbon-intensive materials

As discussed in Chapter 4, there are many low carbon building materials available in the UK marketplace and their use has been increasing. However, it will likely be decades before some of the most promising options achieve widespread adoption. Similarly, design strategies focussing on the improved recovery of materials at end of life are unlikely to yield reductions in the short term. There are no 'silver bullets' and achieving carbon reduction targets will likely require simultaneous uptake of a wide range of alternative materials and design strategies.

Figure 42: Embodied GHG emissions of UK construction sector 1997-2012

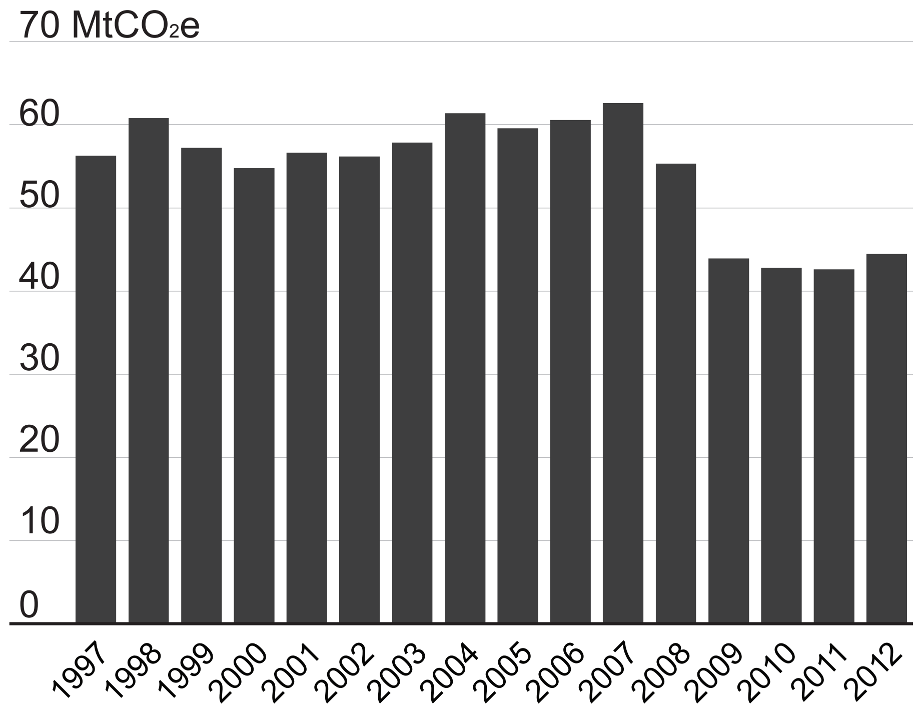
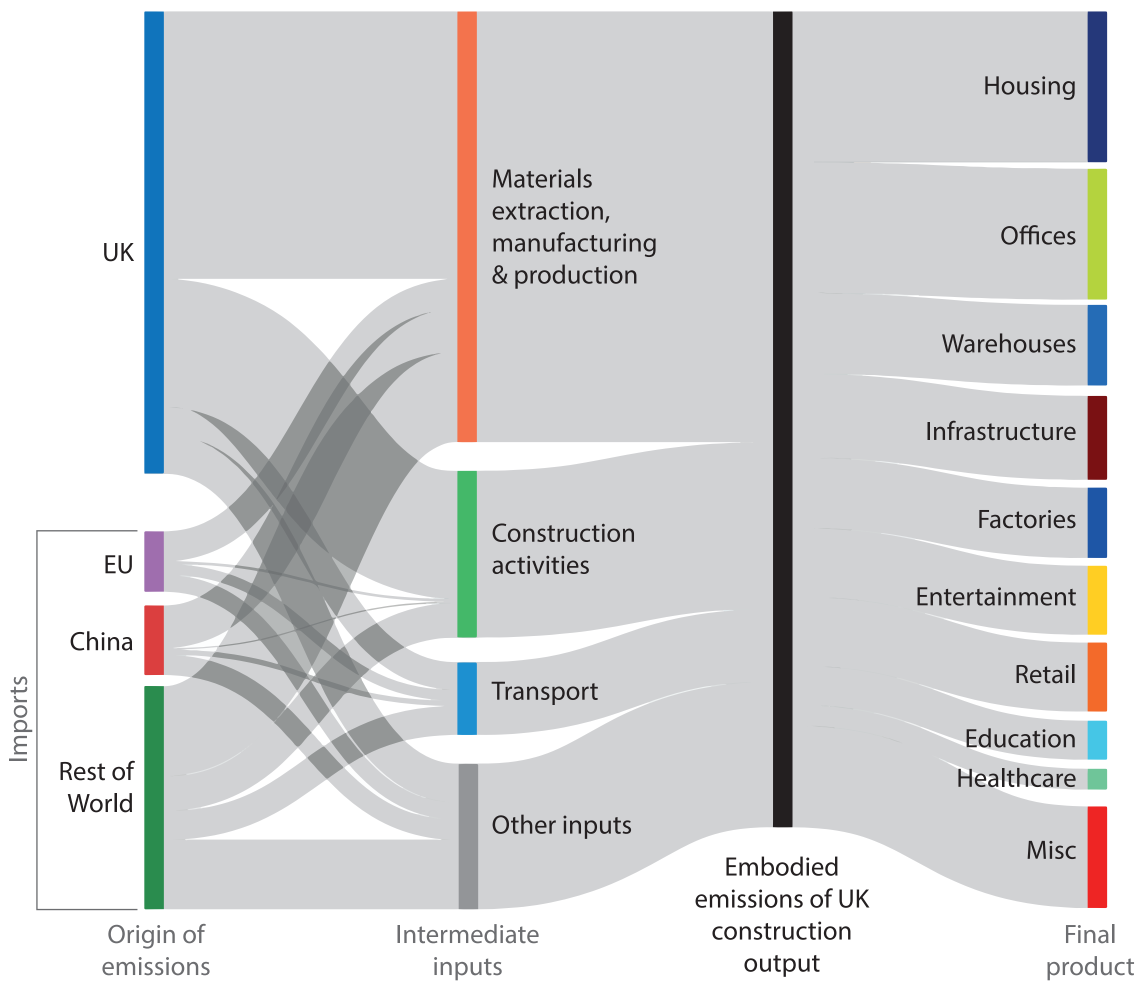


Figure 43: Embodied GHG emissions of UK construction sector in 2007



Research aim 3

Conduct new research to understand the cultural, behavioural, and perceptual barriers to adoption of alternative low carbon building materials amongst industry practitioners involved in design, specification and construction

This research aim was addressed by conducting an industry survey and series of interviews with industry leaders. The following conclusions were drawn.

A multitude of barriers prevent adoption of low carbon materials and additional drivers will be required to stimulate uptake

As highlighted in Chapter 5, in addition to technical and economic barriers, a range of cultural and institutional barriers within the industry prevent greater uptake of alternative low carbon materials. These barriers include: negative perceptions held by clients and colleagues; expectations of additional costs; a shortage of practitioner knowledge, skills and information; a litigious and risk-averse industry culture; and embedded practices that prevent early engagement and effective allocation of responsibility to project participants. If embodied carbon assessment is to become a mainstream concern, provoking a corresponding increase in the use of low carbon building products, then these barriers must be overcome. This will require additional practitioner training; data gathering; contract and tender document changes; and development of a more robust business case. These activities must initially be driven by exemplary clients and supported by greater engagement from the professional institutes. In the longer term regulatory drivers will likely be necessary. Further complementary work must be undertaken to understand the barriers posed by clients and end users.

Research aim 4

Create an analytical framework for translating sector emission reduction targets into project level targets, suitable for use by design teams

This research aim was addressed through the development of a novel model in Matlab. The following conclusions were drawn.

The UK BIEC model provides a basic framework for linking sector and project level embodied carbon targets

The model presented in Chapter 6 provides a first attempt at linking sector level embodied carbon estimates with project level calculations. Whilst the model and subsequent scenario analysis demonstrated the value of such a link, further development, including an expansion of the existing evidence base, will be required to increase the model accuracy and range of applications. This detail can only be realised through greater industry reporting of building LCA data to common repositories. Incentives may be required to ensure more frequent use of existing resources such as the WRAP database.

Research aim 5

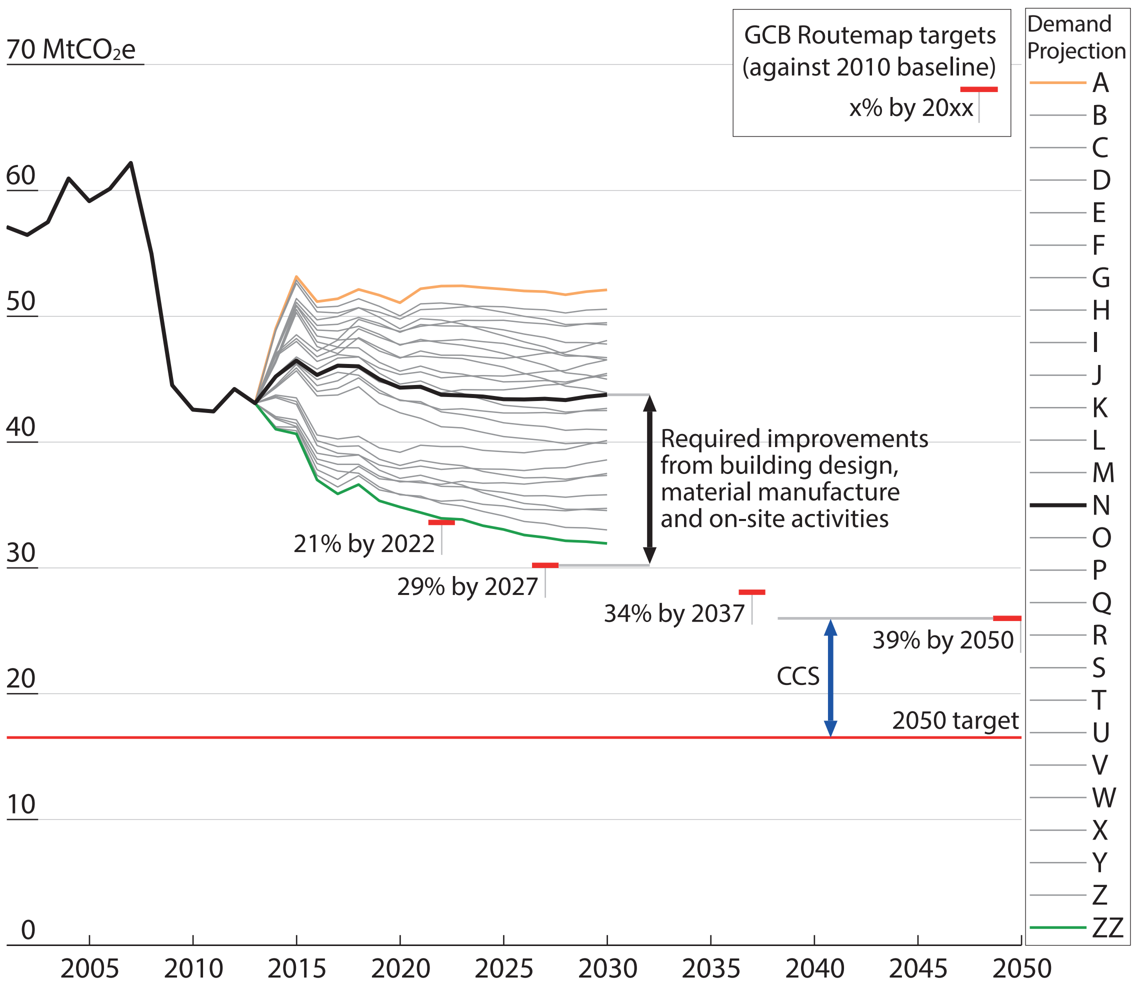
Use the new framework to explore the role for demand reduction in meeting embodied carbon reduction targets

This research aim was addressed by conducting a scenario analysis using the UK BIEC model. The 27 scenarios were indicative of different plausible levels of demand for new buildings and infrastructure. The following conclusions were drawn.

Embodied carbon in construction will play an increasingly significant role in later Carbon Budgets

The range of projections undertaken in Chapter 6 and summarised in Figure 44, illustrate that embodied carbon is likely to occupy a growing share of future Carbon Budgets. Growth in embodied carbon is likely to be driven by increased expenditure on housing and infrastructure. Anticipated reductions in the carbon intensity of the electricity supply are unlikely to fully offset the increase due to growing construction output. Thus, whilst the embodied emissions of building and infrastructure development make only a modest contribution to current Carbon Budgets (5-10%), it is likely to occupy a sizeable proportion of the available

Figure 44: Projected embodied emissions of UK construction 2001-2030 including projected improvements in carbon intensity of electricity supply - relative to targets



carbon space by 2050. Measures supporting reductions could make a significant contribution towards the 5th and later Carbon Budgets. Though long term sectoral targets have yet to be determined, a progressive ramping up of ambition could be considered a plausible response to the recent Paris Agreement. Therefore it is imperative that any long term strategy for the 5th-8th Carbon Budgets considers the role of embodied carbon abatement.

The carbon reduction ambitions of the construction industry will need to respond to a range of external factors

In the long term it is essential that a link is formed between sector level reduction targets and the tangible project level benchmarks utilised by design teams. This is the only way in which the adequacy of current performance can be assessed and future requirements determined. This is particularly crucial given the multiple sources of uncertainty surrounding the scale of reductions required. These sources include the rate of electrical grid decarbonisation, uptake of CCS technology, and global GHG reduction ambitions, all of which are outside the control of the construction industry.

Research aim 6

Identify possible policy responses and industry-led actions that could motivate substantial embodied carbon reduction

This research aim was addressed by collecting potential policies and industry-led actions from the literature, industry debates and a stakeholder workshop. The stakeholder workshop formed part of a broader programme of stakeholder engagement designed to develop potential policy pathways through a participatory approach. Past policy was also critically reviewed to identify lessons for future policy making. The following conclusions were drawn.

Policy responses and industry-led actions must be sequenced within a new approach to construction policy that is more resilient to economic and political circumstances and aligns interests along the supply chain

A review of recent construction policy identified inadequate consideration of policy resilience, sequencing and adaptation. If a repetition of past failures is to be avoided then an alternative approach must be adopted. One such alternative, explored in Chapter 7, is the development of dynamic adaptive policy pathways through a participatory approach. Initial application of this recently developed approach identified a number of weaknesses that must be addressed. Additional work will be required to determine an adaptive long term policy framework that can meet sector carbon reduction targets in the face of deep uncertainty. The example pathways set out in Chapter 7 are a first step in this process.

8.4 Research limitations

All these findings should be considered with due regard for the limitations in underlying data, methodologies, and scope of the research. These limitations are outlined in detail in each chapter and are briefly recapped below.

The UK MRIO and UK BIEC results depend upon the use of financial transactions as proxies where good data on physical flows of materials is not available. The MRIO results are also subject to the customary methodological shortcomings of assumed proportionality, constant prices and so forth. In addition to depending upon outputs from the MRIO, the UK BIEC model depends upon a limited sample of building level LCAs (249) that cannot be deemed fully representative of sector output. Many of the LCAs were conducted to different standards, using different system boundaries and LCI datasets, preventing them from being directly comparable. The forward projections are based upon simplistic assumptions surrounding future demand and do not consider the impacts of likely changes in structure size and form.

The qualitative work assessing barriers to the uptake of low carbon materials was primarily restricted to research amongst design practitioners and did not consider the perspectives of clients, end users or material manufacturers. The work considered buildings produced within the UK and the findings may not be applicable in other markets. The surveys and interviews only gathered the opinions of a small sample of practitioners with particular experience whose views are unlikely to be representative of the industry at large. Similarly, the policy pathways development drew upon input from a select group of practitioners and organisations.

In addition to the reported activities, the author attended or participated in more than 20 industry conferences and events on embodied carbon during the completion of this thesis, and maintains regular contact with interested practitioners across the supply chain. Consequently, although the results are drawn from findings working with small samples, the author believes the results are consistent with the views of a broader group of progressive industry practitioners.

8.5 Remarks and recommendations

The following are a number of remarks and recommendations from the author in response to the collected research results.

Current drivers for embodied carbon reduction are inadequate

There remain no substantive regulatory or widespread client-led drivers for embodied carbon reduction. Whilst moral leaders and firms anticipating a future market have pressed ahead, the current pace of evidence gathering is much too slow to support the required rate of carbon reduction. Additional interventions in the market will be required. This could take the form of a variety of regulatory requirements, incentives or penalties, and should be supported by voluntary cross-industry agreements and the spread of best practice amongst client organisations. It is only through further uptake of embodied carbon assessment that the skeletal business case can be fleshed out. In the long term the strength of this business case will likely determine the pace of uptake and the extent of industry ambition.

The mainstream industry and political discourse on infrastructure development must consider demand reduction

The transition to a low carbon society is fundamentally dependent upon widespread development of supporting infrastructure. Thus the coming decades will see the inevitable completion of a substantial network of new assets. Aside from the contribution that emissions arising from this construction activity will make towards intervening Carbon Budgets, it is also imperative to consider the long term future for those assets. The aggregate level of infrastructure that can be constructed, repaired and maintained within a post-2050 carbon space has yet to be determined. Meanwhile, options that seek to minimise emissions through reducing demand for new infrastructure have been conspicuously absent from mainstream political debate and national carbon reduction strategies. In the absence of revolutionary technologies for material production, the process-based carbon emissions associated with manufacturing key materials for infrastructure development and maintenance may dominate the remaining carbon space beyond 2050. If the UK is to contribute towards meeting the Paris Agreement goal of balancing sources and sinks of GHGs in the second half of this century, then a conversation determining the size and make up of a sustainable long term stock must begin in earnest now. Given the long life spans of buildings and infrastructure, projects currently under construction likely constitute the last generation that will not need to be extended, refurbished or upgraded within carbon budgets that are a fifth of today’s levels.

The development of an embodied carbon community will be critical in disseminating best practice and coordinating industry action

A nascent embodied carbon community is forming, intent on ensuring a prominent role for embodied carbon in any future interpretation of sustainable construction. This community is already responsible for the informal sharing of best practice amongst practitioners and client organisations. However, there is scope for a more formal group backed by a cross-industry institution or public funding to lobby and disseminate best practice and technical guidance. This could be achieved, for example, through the formation of a UKGBC Task Group. The prominence of such a group could help in engaging additional stakeholders and ensure a more coordinated industry response to the issue.

Short term reductions in embodied carbon must be driven by clients. Long term reductions must be driven by policy.

Significant additional regulation of the construction industry is unlikely in the current parliament, with measures addressing embodied carbon largely absent from the political agenda. Consequently reductions in the near term must be driven by client demands. The experience of clients on flagship projects to date has demonstrated that design teams and contractors will respond to ambitious requirements if introduced at the early project stages. Clients with green ambitions must learn from their competitors and be willing to share their experiences. However, whilst exemplary clients and a small cadre of dedicated practitioners may continue to drive best practice, the common perception is that the majority of the industry will only act if forced by regulation.

Such regulation would follow in the wake of a series of high profile policy failures and retractions. Therefore when developing proposals, lessons must be learnt from past outcomes. Greater stakeholder engagement ensuring alignment of interests of all actors along the supply chain, including clients and end users, will be required. Achieving this may require a novel approach to policy making. The DAPP approach, applied in Chapter 7, offers one alternative. However, early applications suggest that further adaptation of the method will be required if it is to be made suitable for developing climate mitigation policy. Irrespective of the particular approach applied, policy interventions addressing embodied carbon must seek to connect short term actions with longer term systemic change, and overcome the current departmental division of construction policy. A robust policy response will likely be both multi-actor and multi-level, featuring a range of mechanisms. This will initially include measures that support embodied carbon calculation and reporting, and embed consideration of embodied carbon in green procurement strategies. Simultaneous measures must stimulate greater generation of product level carbon data. Subsequent measures will likely involve imposing increasing building level requirements upon developers. These requirements can be ratcheted up in response to changing sector targets as 2050 approaches.

8.6 Avenues for future work

Each chapter highlighted a number of unresolved issues and topics requiring further research. These are briefly summarised in the following two sections. The first considers opportunities to further develop work presented in this thesis. The second proposes a number of additional ideas and potential research topics. The author intends to pursue a number of these ideas and would welcome collaborative input.

8.6.1 Further development of work presented in this thesis

Development of UK BIEC model

A number of further developments to the model presented in Chapter 6 could broaden the range of applications whilst improving accuracy and usability. This includes periodic updating of the database to include additional building level LCAs; disaggregation of the building classes; disaggregation of the infrastructure class based on further data collection; and development of a GUI. More detailed scenario analysis could be developed and progress over coming years charted against suggested targets.

Policy pathway development

The stakeholder engagement process described in Chapter 7 will continue, with the intention of further developing a range of policy responses that are consistent with long term targets. This will include mapping of stakeholder interests, influence and narratives; consideration of the preliminary pathways and development of more detailed policy proposals. Additional work will address the scope for adapting existing broad-brush policies to incorporate embodied emissions. Potential opportunities to incorporate embodied emissions into European regulations must also be considered.

8.6.2 Additional research topics

The following topics were not addressed at any length in this thesis but would be worthy of detailed research.

Understanding public perceptions of low carbon materials

This thesis focussed upon barriers to low carbon materials observed within the construction professions. However, public awareness and perceptions of low carbon materials are also crucial in determining uptake and is an equally under-explored research area. Additional studies exploring perceptions of material quality and design amongst current users of buildings made from low carbon materials could shed light on how perceptions can be informed by experience and how these perceptions (and the uptake of low carbon materials) might be affected by designers or public policy.

The diffusion of best practice amongst client organisations

The means by which best practice on embodied carbon is transmitted amongst client organisations in the private sector remains unclear. Anecdotal evidence suggests that adoption of embodied carbon requirements largely occurs as a result of informal communications between counterparts in rival organisations. Particular targets are determined either by gut instinct or extracted from rival development briefs. In some instances targets are introduced in response to suggestions by other project participants. A more formal workshop to support sharing of best practice and development of a state of the art guidance document containing example wording would be welcome. Such a workshop could also provide an opportunity to discuss standardisation of approaches and documentation, such as reporting forms.

The diffusion of best practice amongst Local Authorities

Similarly, Local Authorities currently appear to adopt requirements on an ad hoc basis. According to communications with the author, there is little evidence of Local Authorities sharing best practice through any formalised network or means. Given that at the time of writing 11 Local Authorities had adopted measures, the opportunity to share current practice and discuss a common approach through a workshop or conference could prove helpful. This would not only serve to improve practice amongst these authorities but could support other Local Authorities that have expressed a desire to introduce requirements but currently lack the organisational capacity.

Identifying the link between carbon and cost

Conclusively proving a link between carbon and cost would provide a compelling business case for action and accelerate the industry response in the absence of policy interventions. Quantitative independent data gathering by a cross industry group could shed light on the question of 'in what circumstances does reducing embodied carbon reduce costs?'. The RICS would be the obvious candidate for such a research project.

Making the case for EPD production

Similarly, the provision of clearer information on the costs and financial benefits of EPD production for small and medium sized product manufacturers could greatly increase EPD uptake and the availability of embodied carbon data. An increasing number of large product manufacturers are gathering statistics on the number of requests received for EPDs from clients. Publicly discussing this demand – and any increases over time – may assuage other product manufacturers concerns. Charting this progress publically across a range of products could provide a more compelling case.

The role for EU Resource Efficiency Benchmarks

The development of a framework incorporating common European resource efficiency benchmarks should herald a more standardised approach to data reporting and the increased availability of comparable LCA data. However, it is as yet unclear whether clients across Europe will use these benchmarks for specification, comparison or, indeed, at all. The body of data generated under the proposed framework could be used to identify and spread best practice, but efforts must first be made to distinguish international variations attributable to reporting procedures, climate and design conventions. The stated long term ambition is to make use of the framework in "*policy-setting at various levels*" (EC, 2014); however, specific proposals have yet to emerge. Much work remains to be done in understanding how these benchmarks can be most effectively used by public organisations and policy makers, and what potential these have for driving long term reductions in resource use and embodied carbon.

Understanding the role for material manufacturers in a low carbon future

Whilst detailed roadmaps have investigated the scope for each of the main material producers to reduce carbon emissions through technological changes, a long term strategy for material production in aggregate has yet to emerge. Each producers' plan implicitly assumes continued or growing levels of production against a backdrop of reducing emissions. However, as indicated by the modelling in Chapter 6, it is likely that deep carbon reductions will necessitate greater uptake of alternative materials and absolute reductions in the total volume of materials consumed. This will interfere with the existing dynamics of the sector, potentially reducing the operating scale and market share of principal producers. Materials supply currently depends upon the continued viability of a small number of capital intensive producers that compete for capital within multinational organisations. This model of production already lacks the agility to respond to substantial short term changes in demand, as evidenced by recent changes in the steel market and consequent job losses. The potential impacts upon employment of increased material efficiency or reduced scale and market viability are profound. Therefore any long term strategy for the construction industry must be developed in tandem with a coherent vision of a materials production sector that remains financially viable in a carbon constrained future.

8.7 Final remarks

When work on this thesis commenced in 2012, aside from a select few practitioners, the UK construction industry had only a rudimentary understanding of embodied carbon and no serious strategy for reducing it. During the time it has taken to complete this thesis the industry has issued numerous guidance documents, undertaken hundreds of embodied carbon assessments, organised several high profile events on the topic, lobbied for national policy and seen requirements introduced by a number of Local Authorities. This building momentum represents substantial progress but there are still significant gaps in knowledge and skills and numerous barriers to be overcome. If current advocates for action on embodied carbon are to gain traction, they must garner greater support from cross-industry institutions (such as the UKGBC) and develop the evidence base for cost savings, product and building level carbon data. Significant time and resources were committed to lobbying for the inclusion of embodied carbon as an Allowable Solution, ultimately to no end. However, the commitments made to data submission throughout this process should be honoured and could support future action. Advocates must not be disheartened by apparent disinterest from national policy makers and should pursue opportunities presented at a local and European level. Ongoing EC consultations have the potential to shape embodied carbon policy in the long term. Meanwhile, leading Local Authorities can strengthen requirements in the short term by spreading best practice. However, given their limited resources, sharing of Local Authority experiences may need to be facilitated by a third party. This is one of many supporting roles that academic and industry institutions can play. Similarly, these groups must support improved knowledge transfer from infrastructure to building designers.

In spite of this progress, there is still much work to be done in developing a long term strategy and sufficient drivers. To date, the GCB Routemap represents the only document addressing long term policy options and interim actions for sector climate mitigation that are consistent with stated carbon reduction targets. However, in spite of the Routemap placing an emphasis upon reducing embodied carbon, it contains conspicuously few long term policy suggestions. Actions identified as 'capital carbon priorities', such as "*encourage carbon measurement and reporting*", "*train building professionals to deal with carbon*", "*incentivise measurement and reporting of whole life carbon*", are not assigned to actors. Proposed plans and progress measures do not consider which actors are monitoring or reporting. Advocates for change are not identified and the generation of political and social capital is not addressed in any meaningful way. To a large extent, the policies and funding mechanisms are considered separately from targets, priorities and technical responses in building design and product manufacture. Ultimately, the suggested response to embodied carbon amounts to little more than a list of technical improvements and associated reductions considered in isolation from any changes in attitudes or policy that would support their implementation. If these gaps are to be filled, the industry must engage with the issue in a more coordinated and structured manner, perhaps through the formation of a UKGBC Task Group or a similar collective with cross-industry backing.

It remains difficult to determine what level of reductions in embodied carbon – and corresponding changes in design, materials and skills – will be required in the long term. However, it is clear that if supporting actions are taken soon, then reductions could contribute significantly to meeting the 5th Carbon Budget and beyond. Serious debate around a long term sustainable building and infrastructure stock must begin immediately and policy makers must consider potential interventions. Actions taken over the next decade will determine the viability of meeting UK carbon reduction targets, and will simultaneously shape the nature of the building stock for decades to come. During this time it is imperative that embodied carbon is repositioned as a core component of the international green building agenda.

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Appendix A - Allocation of UK construction supply chain emissions

This appendix outlines how the core figures in Chapter 3 were produced. The following sections address each figure in turn. The MRIO model referred to is described at length in Section 3.4.

Allocation of emissions by activity

Figure 8 representing the breakdown of emissions by activity was produced by the following means. The total emissions attributable to the construction sector in the UK MRIO model were broken down by source sector. Totals for the four principle activities were then assembled by addition of relevant sector sub-totals. The share of emissions from electricity attributable to construction activities was established from a basic first step decomposition. It was assumed that the remainder of emissions from electricity were attributable to 'materials extraction, manufacturing and production'. This is likely a slight overestimate as some of the emissions from electricity will be attributable to 'Other' activities. However, this share is likely very small as energy-intensive material production processes (such as the manufacture of aluminium) are likely to dominate. Even if total emissions from electricity are split proportionally among non-construction activities then the amount attributable to materials would still exceed 45% of the total in a typical year. Table 23 overleaf details the model sectors included in each activity.

Allocation of emissions by end product

Figure 10 representing the emissions breakdown by end product was computed using the UK BIEC model described in Chapter 6. Although, the methodology is not introduced until later in the thesis, results are included in Chapter 3 to provide the reader with a comprehensive overview.

Allocation of emissions by region

Figure 9 representing the breakdown of emissions by region was computed by summating emissions from all sectors by streams and region. In this instance, UK domestic emissions are represented by Stream 1 UK production emissions attributable to UK final consumption. Stream 3a includes emissions embedded in imports through intermediate consumption of UK industry attributable to UK final consumption. By contrast Stream 4a includes emissions embedded in imports direct to final demand attributable to UK final consumption. On this basis all Stream 1 emissions from relevant sectors are allocated to the UK region. Meanwhile Stream 3a EU and Stream 4a EU are summated to provide a total attributed to the EU. With similar totals for Stream 3a and 4a China, and Stream 3a and 4a Rest of World.

Table 23: Allocation of UK MRIO model sectors to construction activities

Activity	Corresponding model sectors
Materials extraction, manufacturing and production	Other mining and quarrying products Wood and of products of wood and cork, except furniture; articles of straw and plaiting materials Paper and paper products Coke and refined petroleum products Paints, varnishes and similar coatings, printing ink and mastics Petrochemicals Rubber and plastic products Manufacture of cement, lime, plaster and articles of concrete, cement and plaster Glass, refractory, clay, other porcelain and ceramic, stone and abrasive products Basic iron and steel Other basic metals and casting Fabricated metal products, excl. machinery and equipment and weapons & ammunition Electrical equipment Emissions from electricity not attributable to construction activities
Construction activities	Direct emissions from construction Waste collection, treatment and disposal services; materials recovery services Rental and leasing services Share of emissions from electricity attributable to construction activities
Transport of people, plant and materials	Rail transport services Land transport services and transport services via pipelines, excluding rail transport Water transport services Air transport services
Other	All other classifications

Appendix B - Literature review details

This appendix contains additional detail on the literature review discussed in Chapter 4. This includes a list of search terms (B1) and common assessment criteria used (B2).

B1. Search terms

Search engines utilised were: Elsevier Science Direct, Elsevier Engineering Village (Compendex and Inspec) and Google Scholar. Additional information was sourced from citation trails, specific institutions, and industry bodies. All search strings are described using Boolean terminology.

Table 24: Search terms for literature review

Database	Search String	Hits	Library Additions
Science Direct	TITLE-ABSTR-KEY (straw) AND TITLE-ABSTR-KEY (construction)	94	9
Science Direct	TITLE-ABSTR-KEY (straw-bale) AND TITLE-ABSTR-KEY (hous*)	8	1
Science Direct	TITLE-ABSTR-KEY (tyre) AND TITLE-ABSTR-KEY (construction)	141	20
Science Direct	TITLE-ABSTR-KEY (tyre) AND TITLE-ABSTR-KEY (hous*)	48	0
Science Direct	TITLE-ABSTR-KEY (earthship)	3	2
Science Direct	TITLE-ABSTR-KEY (rammed earth) AND TITLE-ABSTR-KEY (construction)	18	11
Science Direct	TITLE-ABSTR-KEY (rammed earth) AND TITLE-ABSTR-KEY (hous*)	5	1
Science Direct	TITLE-ABSTR-KEY (earth brick) AND TITLE-ABSTR-KEY (construction)	27	8
Science Direct	TITLE-ABSTR-KEY (cob) AND TITLE-ABSTR-KEY (construction)	14	5
Science Direct	TITLE-ABSTR-KEY (cob) AND TITLE-ABSTR-KEY (hous*)	10	0
Science Direct	ALL FIELDS (novel plastic) AND ALL FIELDS (“sustainable construction”)	47	9
Science Direct	ALL FIELDS (FRP) AND ALL FIELDS (“sustainable construction”)	17	3
Science Direct	ALL FIELDS (composites) AND ALL FIELDS (“sustainable construction”)	286	63
Science Direct	ALL FIELDS (timber-framed) AND ALL FIELDS (“sustainable construction”)	33	10
Science Direct	TITLE-ABSTR-KEY (timber-framed) AND TITLE-ABSTR-KEY (construction)	17	1
Science Direct	TITLE-ABSTR-KEY (timber-framed) AND TITLE-ABSTR-KEY (low carbon)	4	0

Database	Search String	Hits	Library Additions
Science Direct	TITLE-ABSTR-KEY (timber) AND TITLE-ABSTR-KEY (low carbon construction)	7	0
Science Direct	ALL FIELDS ("structural insul* panel*") AND ALL FIELDS (construction)	82	7
Science Direct	ALL FIELDS ("low* carbon") AND ALL FIELDS ("construction techniques")	75	5
Science Direct	TITLE-ABSTR-KEY (carpet reinforcement)	7	0
Science Direct	TITLE-ABSTR-KEY ("low* carbon") AND TITLE-ABSTR-KEY (reinforcement)	14	0
Science Direct	TITLE-ABSTR-KEY (design) AND TITLE-ABSTR-KEY (disassembly)	187	1
Science Direct	TITLE-ABSTR-KEY (construct*) AND TITLE-ABSTR-KEY (disassembl*)	115	1
Science Direct	TITLE-ABSTR-KEY (leas* metal) AND TITLE-ABSTR-KEY (construction)	66	0
Science Direct	TITLE-ABSTR-KEY (rent) AND TITLE-ABSTR-KEY (construction)	53	0
Science Direct	TITLE-ABSTR-KEY (adaptive re-use) AND TITLE-ABSTR-KEY (construction)	13	0
Science Direct	TITLE-ABSTR-KEY ("adaptive re-use")	5	1
Science Direct	TITLE-ABSTR-KEY (adaptive reuse)	76	2
Science Direct	TITLE-ABSTR-KEY ("life extens*") AND TITLE-ABSTR-KEY (construction)	18	2
Science Direct	TITLE-ABSTR-KEY (refurbishment) AND TITLE-ABSTR-KEY (construction)	37	3
Science Direct	TITLE-ABSTR-KEY (refurbish*) AND TITLE-ABSTR-KEY (struct*)	59	4
Science Direct	TITLE-ABSTR-KEY (high* grade materials) AND TITLE-ABSTR-KEY (construction)	111	3
Science Direct	TITLE-ABSTR-KEY (agricultural waste) AND TITLE-ABSTR-KEY (concrete)	25	5
Science Direct	TITLE-ABSTR-KEY (demolition waste) AND TITLE-ABSTR-KEY (concrete)	120	57
Science Direct	TITLE-ABSTR-KEY (consumer waste) AND TITLE-ABSTR-KEY (concrete)	14	3
Science Direct	TITLE-ABSTR-KEY (GGBS) AND TITLE-ABSTR-KEY (concrete)	66	15
Science Direct	TITLE-ABSTR-KEY (fly ash concrete) AND TITLE-ABSTR-KEY (low carbon)	27	7
Science Direct	TITLE-ABSTR-KEY (hollow* concrete) AND TITLE-ABSTR-KEY (carbon)	23	1
Science Direct	TITLE-ABSTR-KEY (construction material*) AND TITLE-ABSTR-KEY (low CO2)	72	12
Science Direct	TITLE-ABSTR-KEY (construction material*) AND TITLE-ABSTR-KEY (low carbon)	194	7

Database	Search String	Hits	Library Additions
Compendex	(((straw) WN KY) AND ((building materials) WN CV))	76	30
Inspec	(((straw) WN KY) AND ((building materials) WN CV))	30	12
Compendex	(((tyre) WN KY) AND ((building materials) WN CV))	14	7
Inspec	(((tyre) WN KY) AND ((building materials) WN CV))	57	30
Compendex	((earthship) WN KY)	6	6
Inspec	((earthship) WN KY)	5	5
Compendex	(((rammed earth) WN KY) AND ((building materials) WN CV))	50	30
Inspec	(((rammed earth) WN KY) AND ((building materials) WN CV))	19	10
Compendex	(((earth brick) WN KY) AND ((building materials) WN CV))	45	13
Inspec	(((earth brick) WN KY) AND ((building materials) WN CV))	9	3
Compendex	(((cob) WN KY) AND ((building materials) WN CV))	14	7
Inspec	(((cob) WN KY) AND ((building materials) WN CV))	9	7
Compendex	((((FRP) WN KY) AND ((building materials) WN CV)) AND ((sustainable) WN All fields))	25	6
Inspec	((((FRP) WN KY) AND ((building materials) WN CV)) AND ((sustainable) WN All fields))	4	1
Compendex	((((timber) WN KY) AND ((building materials) WN CV)) AND ((sustainable) WN All fields))	63	28
Inspec	((((timber) WN KY) AND ((building materials) WN CV)) AND ((sustainable) WN All fields))	11	1
Compendex	(((SIP) WN KY) AND ((building materials) WN CV))	20	8
Inspec	(((SIP) WN KY) AND ((building materials) WN CV))	2	1
Compendex	(((low carbon) WN KY) AND ((building materials) WN CV))	20	9
Inspec	(((low carbon) WN KY) AND ((building materials) WN CV))	157	35
Compendex	(((carpet reinforcement) WN KY) AND ((building materials) WN CV))	12	2
Inspec	(((carpet reinforcement) WN KY) AND ((building materials) WN CV))	1	0
Compendex	(((mat reinforcement) WN KY) AND ((building materials) WN CV))	22	2
Inspec	(((mat reinforcement) WN KY) AND ((building materials) WN CV))	9	0
Compendex	(((roll reinforcement) WN KY) AND ((building materials) WN CV))	27	0
Inspec	(((roll reinforcement) WN KY) AND ((building materials) WN CV))	1	0
Compendex	((((low carbon) WN KY) AND ((reinforcement) WN KY)) AND ((building materials) WN CV))	134	3

Database	Search String	Hits	Library Additions
Inspec	((((low carbon) WN KY) AND ((reinforcement) WN KY)) AND ((building materials) WN CV))	27	1
Compendex	(((agricultural wastes) WN CV) AND ((concrete) WN KY))	52	16
Inspec	(((agricultural waste) WN KY) AND ((concrete) WN KY))	26	10
Compendex	((((demolition) WN CV) AND ((concrete) WN KY)) AND ((waste) WN KY))	174	92
Inspec	(((demolition waste) WN KY) AND ((concrete) WN KY))	104	56
Compendex	((((consumer waste) WN KY) AND ((concrete) WN KY)) AND ((wastes) WN CV))	54	25
Inspec	(((consumer waste) WN KY) AND ((concrete) WN CV))	21	9
Compendex	((((GGBS) WN KY) AND ((concrete) WN KY)) AND ((sustainable) WN KY))	22	14
Inspec	((((GGBS) WN KY) AND ((concrete) WN KY)) AND ((sustainable) WN KY))	3	3
Compendex	((((GGBS) WN KY) AND ((concrete) WN KY)) AND ((low carbon) WN KY))	4	2
Inspec	((((GGBS) WN KY) AND ((concrete) WN KY)) AND ((low carbon) WN KY))	1	0
Compendex	((((fly ash) WN CV) AND ((concrete) WN KY)) AND ((sustainable) WN KY))	194	121
Inspec	((((fly ash) WN CV) AND ((concrete) WN KY)) AND ((sustainable) WN KY))	47	21
Compendex + Inspec	((((hollow core) WN KY) AND ((concrete) WN KY)) AND ((sustainable) WN KY))	10	3
Inspec	((((hollow core) WN KY) AND ((concrete) WN KY)) AND ((low carbon) WN KY))	2	0
Compendex	(((design for disassembly) WN KY) AND ((construction) WN CV))	34	14
Inspec	(((design for disassembly) WN KY) AND ((construction) WN CV))	10	4
Compendex	(((re-use) WN KY) AND ((construction) WN CV))	58	27
Inspec	(((re-use) WN KY) AND ((construction) WN CV))	11	6
Compendex	(((leasing) WN KY) AND ((construction) WN CV))	90	0
Compendex	(((life extension) WN KY) AND ((construction) WN CV))	176	14
Inspec	(((life extension) WN KY) AND ((construction) WN CV))	34	2
Compendex	(((refurb*) WN KY) AND ((construction) WN CV))	167	20
Inspec	(((refurb*) WN KY) AND ((construction) WN CV))	55	10
Compendex	((((high grade material) WN KY) AND ((construction) WN CV)) AND ((sustainable) WN KY))	10	2

Database	Search String	Hits	Library Additions
Inspec	((((high grade material) WN KY) AND ((construction) WN CV)) AND ((sustainable) WN KY))	1	0
Compendex	((((high grade) WN KY) AND ((construction) WN CV)) AND ((low carbon) WN KY))	13	1
Inspec	((((high grade) WN KY) AND ((construction) WN CV)) AND ((low carbon) WN KY))	4	0
Google Scholar	straw bale construction	20	2
Google Scholar	tyre construction	25	5
Google Scholar	earthship	4	1
Google Scholar	rammed earth construction	74	8
Google Scholar	earth brick	61	0
Google Scholar	cob construction	7	0
Google Scholar	FRP sustainable	20	4
Google Scholar	timber low carbon construction	11	7
Google Scholar	timber sustainable construction	49	2
Google Scholar	carpet reinforcement	4	0
Google Scholar	roll out reinforcement	2	0
Google Scholar	low carbon reinforcement construction	24	0
Google Scholar	disassembly construction	38	1
Google Scholar	adaptive reuse construction	14	0
Google Scholar	leasing construction	25	0
Google Scholar	leasing metal	2	0
Google Scholar	life extension construction	69	5
Google Scholar	high grade sustainable construction	9	0
Google Scholar	hollow concrete construction	68	4
Google Scholar	low carbon materials construction	254	8

B2. Common assessment criteria

The suitability of each alternative material, technology and practice was qualitatively assessed against a common set of criteria. These criteria reflect the ability of each option to replace the current predominant material mix.

Physical performance

Any viable alternative must provide comparable performance to current materials, or at least sufficient performance relative to building codes. Structural materials must provide adequate strength, durability and ductility to provide safe and functional structures. The thermal performance of materials is often also of critical importance in ensuring a suitable internal climate and minimising operational emissions from space heating. Moreover, alternatives must ensure an adequate service life with acceptable maintenance requirements.

Environmental impacts

Implicit in the premise of the review is the assumption that all the options considered offer, at least in some applications, a reduced global warming potential relative to the current material mix. However, whilst a particular option may offer a considerable reduction in associated carbon emissions, it may produce another hazardous waste stream or require increased water use in production. Other than options that aim to reduce demand, all alternatives are likely to result in some degree of environmental impact. It is important to acknowledge these impacts and to consider them relative to those of the materials they would displace. Though these impacts are not discussed in the chapter summary, they were considered in assembling the rough review documents.

Economic competitiveness

The competitive nature of the construction industry generally necessitates low profit margins. The conservative nature of the industry means that in practice firms are unlikely to switch to new options unless they are of benefit in financial terms. Therefore the price of materials is often a decisive factor in design decisions. Though it should be remembered that, on most projects, the cost of raw materials represents a small proportion of the overall project value. In many cases, the value of an alternative material or technology is not directly manifested in the material purchase price. Consequent reductions in the project schedule or reduced need for expensive plant and skilled labour can often lead to overall reductions in project costs. Predictability of price is also important, particularly on projects with long programmes. Therefore, the viability of any alternative must be considered as part of total project estimates on a life cycle basis.

Social acceptability

A key consideration when judging the success of any project is the satisfaction of the end users. When considerable changes in construction materials and practices are required there will undoubtedly be some opposition. The assessment of social acceptability is likely to vary significantly depending on the nature of the option under consideration. Purely technical solutions that affect designers or contractors but have no direct impact upon end users are likely to confront fewer problems of social acceptance. Solutions that significantly alter the end user experience or place additional requirements upon end users may meet with more opposition. Negative perceptions may also be encountered with the use of unfamiliar materials or controversial waste streams.

Ease of implementation

Some alternatives are more radical than others and necessitate wholesale changes in procurement, design, or construction processes. New materials may require additional plant or skills not currently available to firms, or result in significant changes to typical project schedules. Other options, such as minor amendments to manufacturing processes, may impact less on current practices and, consequently, may be more easily implemented with less resistance from the professions. Solutions that are simple to implement, and fit easily within existing workflows, also have the potential to make a more immediate impact upon material use. This immediacy is particularly important within the timeframe of this review.

Sufficiency of supply chain

If an alternative is to be deployed at scale then it must already possess, or have the potential to form, a suitable supply chain. This requires both a reliable source of materials and a sufficient supply of skilled practitioners to implement these solutions. In assessing the scope for adoption of alternative materials it may be necessary to approximate the maximum volume of materials that could be produced from available production facilities and waste flows. However, if these options were widely implemented, flows could change over time, and additional material may be imported to meet demand. It is incredibly difficult to accurately predict the future availability of supply but this does not diminish its importance in determining the potential scale of uptake. Likewise, it is difficult to assess existing skill levels and numbers of practitioners, and predict how these could change over the coming decades. Options that depend upon present materials and skills should be viewed favourably.

Readiness

In the construction sector iconic projects and case studies play a critical role in shaping future trends. There are simply too many projects undertaken in any given year for any individual practitioner to understand the full range of methods and materials in use. Knowledge of new materials and practices is often widely disseminated after their use in a prominent or unusual project. Experience is also gained, and improvements made, from repeated application of any new solution. If any option is to achieve significant uptake then completed examples must exist for practitioners to turn to. Some options under consideration in this review already sport many examples, others have yet to leave the laboratory. When assessing 'readiness' it is necessary to look at the current stage of development and for successful examples of its application in practice. It is also necessary to critically examine the failings of past examples and identify any improvements that have been or need to be made.

Appendix C - Survey questions and results

This appendix contains the full survey questions (C1) and results (C2). A summary of these results is presented in Chapter 5.

C1. Survey questions

The following text is a transcription of all survey questions and possible responses. In all instances where respondents were asked to choose from a prescribed list an opportunity was provided to add other options and adjacent comments for each example material. Possible answers were generated from the literature review and pilot survey testing.

Q1 What is your job title?

Q2 What is the typical project role of your employer?

- ◊ Architect
- ◊ Contractor
- ◊ Engineer
- ◊ Project Management
- ◊ Quantity Surveyor
- ◊ Sustainability Consultant
- ◊ Other ______________________

Q3 In which country do you normally work?

- ◊ United Kingdom of Great Britain and Northern Ireland
- ◊ Afghanistan
- ◊ Albania
- ◊ Algeria

Etc.

Q4 For how many years have you worked in construction?

- ◊ Less than 2 years
- ◊ 2-5 years
- ◊ 6-10 years
- ◊ 11-15 years
- ◊ 16-20 years
- ◊ Over 20 years

Q5 Approximately how many staff does your company directly employ?

- ◊ 1 (self-employed)
- ◊ 2-13
- ◊ 14-34
- ◊ 35-59
- ◊ 60-114
- ◊ 115-599
- ◊ 600-1199
- ◊ 1200+
- ◊ Don't know

Q6 How much influence do you have over the selection of materials and construction products on a typical project?

- ◊ No influence
- ◊ Little influence
- ◊ Some influence
- ◊ Strong influence
- ◊ Primary influence

Q7 Who do you believe has the greatest influence over material and construction product selection on a typical project?

	No influence	Little influence	Some influence	Strong influence	Primary influence
Architect	◊	◊	◊	◊	◊
Civil/structural engineer	◊	◊	◊	◊	◊
Client	◊	◊	◊	◊	◊
Contractor	◊	◊	◊	◊	◊
M&E/services engineer	◊	◊	◊	◊	◊
Planner	◊	◊	◊	◊	◊
Project manager	◊	◊	◊	◊	◊
Quantity surveyor	◊	◊	◊	◊	◊
Sustainability consultant	◊	◊	◊	◊	◊

Q8 Please rank who you believe should ultimately be responsible for minimising the embodied carbon emissions on a project? Click and drag to change order. 1 is most important, and 9 is least important.

_______ Architect
_______ Civil/structural engineer
_______ Client
_______ Contractor
_______ M&E/services engineer
_______ Planner
_______ Project manager
_______ Quantity surveyor
_______ Sustainability consultant

Q9 What is your knowledge of the following materials and construction products?

	Used on project(s)	Aware of but not used	Little or no knowledge of
Brettstapel	◊	◊	◊
Cross Laminated Timber (CLT)	◊	◊	◊
Structural Insulated Panels (SIPs)	◊	◊	◊
Straw bale (either load bearing, infill or modular)	◊	◊	◊
Rammed earth	◊	◊	◊
Unfired brick	◊	◊	◊
Cob	◊	◊	◊
Adobe	◊	◊	◊
Hemp (including hemp-lime composites)	◊	◊	◊
Limecrete	◊	◊	◊
Cardboard (tubes or panels)	◊	◊	◊
Ethylene tetrafluoroethylene (ETFE)	◊	◊	◊
Inorganic Fibre Reinforced Polymers (FRP)	◊	◊	◊
Geopolymer concrete	◊	◊	◊
Concrete containing agricultural wastes (e.g. rice husks, vegetable fibres or nut shells)	◊	◊	◊
Concrete containing consumer wastes (e.g. plastics, glass or tyres)	◊	◊	◊
Concrete containing construction and demolition wastes	◊	◊	◊

	Used on project(s)	Aware of but not used	Little or no knowledge of
Concrete containing industrial wastes (e.g. steel slag, sewage sludge ash, silica fume)	◊	◊	◊
Precast hollowcore floor slabs	◊	◊	◊
Optimised roll-out reinforcement meshes (e.g. BAMTEC or ROLLMAT)	◊	◊	◊
Recycled aggregates	◊	◊	◊
Recycled plastic lumber	◊	◊	◊
Reclaimed steel	◊	◊	◊
Reclaimed timber	◊	◊	◊

For all materials for which 'Used on project(s)' is selected in Q9

Q10 How often have you used each of these materials?

◊ On a single project
◊ On multiple projects
◊ Material is routinely used or considered on all projects

Q11 How would you rate your experience of using each of these materials?

◊ Mostly negative
◊ Somewhat negative
◊ Neither positive or negative
◊ Somewhat positive
◊ Mostly positive

Space for comments

Q12 Thinking about the projects on which you used these materials. Why did you choose to use each material?

◊ Low cost
◊ Client required it
◊ Architect, engineer or contractor required it
◊ Fits with company ethos
◊ Felt morally obliged to use low impact material
◊ Offered best structural performance
◊ Offered low operating costs
◊ Earned points towards assessment scheme (e.g. BREEAM, LEED)
◊ Reduced construction schedule

- ◊ Desirable aesthetics
- ◊ Improved 'health' of building
- ◊ Regulatory requirement
- ◊ Other

Space for comments

For all materials for which 'On a single project' is selected in Q10

Q13a Would you use these materials again?

- ◊ Yes
- ◊ No

Space for comments

For all materials for which 'No' is selected

Q13b Why would you not consider using these materials again?

Space for comments

For all materials for which 'Aware of but not used' is selected in Q9

Q14 You stated that you are aware of but have not used the following materials on a project. Why have you chosen not to use these materials?

- ◊ Not appropriate for type of projects I am typically engaged in
- ◊ Too costly
- ◊ Negative experiences of colleagues
- ◊ Negative perceptions held by clients
- ◊ Negative perceptions held by other project professionals
- ◊ Insufficient structural or thermal performance
- ◊ Concerns about durability
- ◊ Lack of technical knowledge or training
- ◊ Low availability of materials
- ◊ Low availability of skilled labour
- ◊ Too time consuming to design with
- ◊ Lack of established standards
- ◊ Lack of design guides and tools
- ◊ Lack of case studies or demonstration projects
- ◊ Insufficient fit with culture of clients
- ◊ Insurance issues
- ◊ Other

Space for comments

Q15 Thinking more generally about alternative materials in construction, how important do you believe the following factors are in preventing their use?

	Not at all important	Somewhat unimportant	Somewhat important	Very important	Extremely important	Comments
High costs	◊	◊	◊	◊	◊	
Institutional culture and established practice	◊	◊	◊	◊	◊	
Insufficient design or performance information	◊	◊	◊	◊	◊	
Lack of design knowledge and skills	◊	◊	◊	◊	◊	
Shortage of skilled labour	◊	◊	◊	◊	◊	
Lack of regulation	◊	◊	◊	◊	◊	
Lack of demonstration projects	◊	◊	◊	◊	◊	
Time constraints	◊	◊	◊	◊	◊	
Bad press	◊	◊	◊	◊	◊	
Conservative nature of clients	◊	◊	◊	◊	◊	
Negative perceptions of industry	◊	◊	◊	◊	◊	
Other	◊	◊	◊	◊	◊	
Other	◊	◊	◊	◊	◊	

Q16 How important do you believe the following developments could be in encouraging greater use of alternative materials and construction products?

	Not at all important	Somewhat unimportant	Somewhat important	Very important	Extremely important	Comments
Higher value in assessment schemes (e.g. BREEAM)	◊	◊	◊	◊	◊	
Regulation limiting embodied carbon in construction	◊	◊	◊	◊	◊	
Reductions in material cost	◊	◊	◊	◊	◊	
More environmentally conscious clients	◊	◊	◊	◊	◊	
More information on material performance and design	◊	◊	◊	◊	◊	
More demonstration projects and case studies	◊	◊	◊	◊	◊	
Training on designing with alternative materials	◊	◊	◊	◊	◊	
Other	◊	◊	◊	◊	◊	
Other	◊	◊	◊	◊	◊	

Q17 Is there anything else you would like to add about any of the topics discussed?

Q18 Would you be willing to participate in future surveys, interviews or focus groups that explore the topics discussed in more detail?

- ◊ Yes
- ◊ No

If answer 'Yes' is selected

Q19 You stated that you were willing to participate in future studies. Please provide your preferred contact details.

C2. Survey results

The following pages contain amalgamated responses to the survey. Owing to the extensive nature of the additional comments returned by participants these have been omitted from this summary. If these are of interest please contact the author. Graphical interpretations of these results can be found in Chapter 5. Potentially sensitive information including job titles and contact information have also been omitted to preserve the anonymity of respondents.

Q2 What is the typical project role of your employer?

Answer	Response
Architect	15
Contractor	3
Engineer	13
Project Management	4
Quantity Surveyor	0
Sustainability Consultant	14
Other	9

'Other' included those involved with research, development, trade associations or construction product manufacture and supply.

Q3 In which country do you normally work?

Answer	Response	%
United Kingdom	36	77%
Australia	1	2%
Colombia	1	2%
Denmark	1	2%
Greece	1	2%
Hong Kong (S.A.R.)	1	2%
Hungary	1	2%
Ireland	1	2%
Romania	1	2%
Spain	2	4%
United States of America	1	2%
Total	**47**	**100%**

Q4 For how many years have you worked in construction?

Answer	Response	%
Less than 2 years	4	9%
2-5 years	19	40%
6-10 years	5	11%
11-15 years	7	15%
16-20 years	3	6%
Over 20 years	9	19%
Total	**47**	**100%**

Q5 Approximately how many staff does your company directly employ?

Answer	Response	%
1 (self-employed)	6	13%
2-13	11	23%
14-34	2	4%
35-59	4	9%
60-114	1	2%
115-599	6	13%
600-1199	5	11%
1200+	11	23%
Don't Know	1	2%
Total	**47**	**100%**

Q6 How much influence do you have over the selection of materials and construction products on a typical project?

Answer	Response	%
No influence	6	13%
Little influence	6	13%
Some influence	13	28%
Strong influence	16	34%
Primary influence	6	13%
Total	**47**	**100%**

Q7 Who do you believe has the greatest influence over material and construction product selection on a typical project?

	No influence	Little influence	Some influence	Strong influence	Primary influence	Total Responses	Mean
Architect	0	1	11	27	8	47	3.89
Civil/structural engineer	0	3	20	19	5	47	3.55
Client	0	8	11	19	9	47	3.62
Contractor	1	7	16	18	5	47	3.40
M&E/services engineer	3	19	24	1	0	47	2.49
Planner	4	13	23	6	1	47	2.72
Project manager	8	19	14	5	1	47	2.40
Quantity surveyor	4	17	14	7	5	47	2.83
Sustainability consultant	2	12	22	11	0	47	2.89

Q8 Please rank who you believe should ultimately be responsible for minimising the embodied carbon emissions on a project? Click and drag to change order. 1 is most important, and 9 is least important.

	1	2	3	4	5	6	7	8	9	Total
Architect	17	14	5	5	6	0	0	0	0	47
Civil/structural engineer	4	13	10	4	8	4	3	0	1	47
Client	12	6	11	6	2	2	1	2	5	47
Contractor	1	2	7	10	10	5	5	3	4	47
M&E/services engineer	0	1	3	6	11	7	9	6	4	47
Planner	3	1	1	5	4	10	11	8	4	47
Project manager	0	3	1	2	2	8	12	12	7	47
Quantity surveyor	0	0	2	3	3	4	6	15	14	47
Sustainability consultant	10	7	7	6	1	7	0	1	8	47
Total responses	47	47	47	47	47	47	47	47	47	

Q9 What is your knowledge of the following materials and construction products?

		Used on project(s)	Aware of but not used	Little or no knowledge of
1	Brettstapel	4	9	31
2	Cross Laminated Timber (CLT)	17	22	5
3	Structural Insulated Panels (SIPs)	11	22	11
4	Straw bale	11	28	5
5	Rammed earth	10	24	10
6	Unfired brick	4	27	13
7	Cob	5	24	15
8	Adobe	5	27	12
9	Hemp (including hemp-lime composites)	11	21	12
10	Limecrete	9	27	8
11	Cardboard (tubes or panels)	3	25	16
12	Ethylene tetrafluoroethylene (ETFE)	5	16	23
13	Inorganic Fibre Reinforced Polymers (FRP)	5	15	24
14	Geopolymer concrete	7	11	26
15	Concrete containing agricultural wastes	5	18	21
16	Concrete containing consumer wastes	10	20	14
17	Concrete containing construction and demolition wastes	14	16	14
18	Concrete containing industrial wastes	17	12	15
19	Precast hollowcore floor slabs	17	12	15
20	Optimised roll-out reinforcement meshes	7	9	28
21	Recycled aggregates	22	19	3
22	Recycled plastic lumber	6	19	19
23	Reclaimed steel	15	24	5
24	Reclaimed timber	19	18	7

Q10 How often have you used each of these materials?

		On a single project	On multiple projects	Material is routinely used or considered on all projects	Total Responses
1	Brettstapel	1	2	0	3
2	Cross Laminated Timber (CLT)	6	3	3	12
3	Structural Insulated Panels (SIPs)	1	5	1	7
4	Straw bale	4	3	1	8
5	Rammed earth	5	2	0	7
6	Unfired brick	1	0	0	1
7	Cob	2	0	0	2
8	Adobe	1	2	0	3
9	Hemp (including hemp-lime composites)	7	1	1	9
10	Limecrete	5	0	1	6
11	Cardboard (tubes or panels)	1	1	0	2
12	Ethylene tetrafluoroethylene (ETFE)	3	1	0	4
13	Inorganic Fibre Reinforced Polymers (FRP)	1	4	0	5
14	Geopolymer concrete	2	1	1	4
15	Concrete containing agricultural wastes	2	2	0	4
16	Concrete containing consumer wastes	4	3	1	8
17	Concrete containing construction and demolition wastes	5	3	4	12
18	Concrete containing industrial wastes	4	3	8	15
19	Precast hollowcore floor slabs	3	3	6	12
20	Optimised roll-out reinforcement meshes	2	2	0	4
21	Recycled aggregates	3	6	8	17
22	Recycled plastic lumber	0	2	2	4
23	Reclaimed steel	2	6	4	12
24	Reclaimed timber	3	7	3	13
	TOTALS	68	62	44	174

Q11 How would you rate your experience of using each of these materials?

		Mostly negative	Somewhat negative	Neither positive or negative	Somewhat positive	Mostly positive	Total Responses
1	Brettstapel	0	0	0	3	0	3
2	Cross Laminated Timber (CLT)	0	0	0	6	6	12
3	Structural Insulated Panels (SIPs)	0	0	1	4	2	7
4	Straw bale	0	0	3	3	2	8
5	Rammed earth	0	3	1	0	3	7
6	Unfired brick	0	0	1	0	0	1
7	Cob	0	0	2	0	0	2
8	Adobe	0	0	1	0	2	3
9	Hemp (including hemp-lime composites)	0	0	2	6	1	9
10	Limecrete	0	0	1	5	0	6
11	Cardboard (tubes or panels)	0	0	1	1	0	2
12	Ethylene tetrafluoroethylene (ETFE)	0	1	1	1	1	4
13	Inorganic Fibre Reinforced Polymers (FRP)	0	1	2	2	0	5
14	Geopolymer concrete	0	0	2	1	1	4
15	Concrete containing agricultural wastes	0	1	1	0	2	4
16	Concrete containing consumer wastes	0	0	4	0	4	8
17	Concrete containing construction and demolition wastes	0	1	6	2	3	12
18	Concrete containing industrial wastes	0	0	3	2	10	15
19	Precast hollowcore floor slabs	0	1	4	5	2	12
20	Optimised roll-out reinforcement meshes	0	0	2	1	1	4
21	Recycled aggregates	0	1	5	3	8	17
22	Recycled plastic lumber	0	0	1	2	1	4
23	Reclaimed steel	0	2	3	3	4	12
24	Reclaimed timber	0	1	2	6	4	13
	TOTALS	0	12	49	56	57	174

Q12 Thinking about the projects on which you used these materials. Why did you choose to use each material?

	Low cost	Client required it	Architect, engineer or contractor required it	Fits with company ethos	Felt morally obliged to use low impact material	Offered best structural performance	Offered low operating costs	Earned points towards assessment scheme (e.g. BREEAM, LEED)	Reduced construction schedule	Desirable aesthetics	Improved 'health' of building	Regulatory requirement	Total Responses
1	0	1	1	2	1	1	0	1	2	1	0	0	10
2	0	7	4	4	4	4	0	7	4	2	3	1	40
3	2	1	0	0	2	2	1	1	4	0	0	0	13
4	2	5	3	3	1	0	3	2	0	2	3	0	24
5	1	3	1	1	2	0	1	0	0	3	1	0	13
6	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	2	0	0	0	0	0	0	0	0	0	0	2
8	0	0	0	1	0	0	1	0	0	1	0	0	3
9	0	6	2	2	2	0	1	2	0	2	3	0	20
10	0	3	3	1	2	0	0	0	0	2	1	0	12
11	0	0	0	0	0	0	0	1	1	0	0	0	2
12	1	2	2	1	0	1	2	0	0	1	0	0	10
13	0	1	3	0	0	2	1	0	0	0	0	0	7
14	0	0	0	0	0	2	0	1	0	0	0	0	3
15	0	2	0	0	1	0	0	1	0	1	0	0	5
16	2	2	2	1	3	2	1	1	1	0	0	0	15
17	1	2	2	2	4	2	0	3	0	0	1	0	17
18	2	2	2	3	7	5	1	5	0	1	1	0	29
19	3	0	3	0	1	5	3	0	3	1	1	0	20
20	0	0	0	0	1	0	1	1	1	0	0	0	4
21	4	2	4	5	7	1	1	6	1	0	1	1	33
22	0	0	0	1	2	1	0	0	0	0	0	0	4
23	5	0	3	2	5	3	1	4	1	1	0	1	26
24	2	3	1	3	4	1	0	5	1	3	1	1	25
Total	25	44	36	32	49	32	18	41	19	21	16	4	337

Q13a Would you use these materials again?

		Yes	No
1	Brettstapel	1	0
2	Cross Laminated Timber (CLT)	6	0
3	Structural Insulated Panels (SIPs)	1	0
4	Straw bale	4	0
5	Rammed earth	3	2
6	Unfired brick	1	0
7	Cob	1	1
8	Adobe	1	0
9	Hemp (including hemp-lime composites)	7	0
10	Limecrete	5	0
11	Cardboard (tubes or panels)	1	0
12	Ethylene tetrafluoroethylene (ETFE)	3	0
13	Inorganic Fibre Reinforced Polymers (FRP)	1	0
14	Geopolymer concrete	2	0
15	Concrete containing agricultural wastes	2	0
16	Concrete containing consumer wastes	4	0
17	Concrete containing construction and demolition wastes	5	0
18	Concrete containing industrial wastes	3	1
19	Precast hollowcore floor slabs	1	2
20	Optimised roll-out reinforcement meshes	2	0
21	Recycled aggregates	3	0
22	Recycled plastic lumber	0	0
23	Reclaimed steel	2	0
24	Reclaimed timber	2	1

Q14 You stated that you are aware of but have not used the following materials on a project. Why have you chosen not to use these materials?

	Not appropriate for type of projects I am typically engaged in	Too costly	Negative experiences of colleagues	Negative perceptions held by clients	Negative perceptions held by other project professionals	Insufficient structural or thermal performance	Concerns about durability	Lack of technical knowledge or training	Low availability of materials	Low availability of skilled labour	Too time consuming to design with	Lack of established standards	Lack of design guides and tools	Lack of case studies or demonstration projects	Insufficient fit with culture of clients	Insurance issues	Total Responses
1	2	1	0	0	0	0	0	3	1	1	0	0	1	1	1	0	11
2	10	3	0	0	1	1	1	2	0	0	0	3	2	1	0	1	25
3	5	0	1	0	2	1	3	3	0	0	0	1	2	1	1	0	20
4	15	1	0	2	3	2	4	0	1	0	2	2	1	1	2	2	38
5	11	2	0	3	4	2	3	4	1	4	2	3	2	1	3	2	47
6	11	2	0	0	3	1	4	3	2	1	1	2	3	2	4	1	40
7	12	1	1	2	4	3	3	3	2	2	1	3	2	1	3	2	45
8	15	1	1	2	4	2	4	4	1	2	1	4	2	1	3	2	49
9	6	1	0	1	3	1	1	1	2	1	2	4	2	1	1	1	28
10	7	1	1	1	4	2	3	2	3	2	1	1	2	2	0	0	32
11	12	1	0	1	1	2	6	4	0	1	1	3	1	0	3	2	38
12	2	1	0	0	1	0	2	5	0	0	0	1	0	0	2	0	14
13	1	0	0	0	0	1	0	4	1	1	0	0	0	0	0	0	8
14	0	1	0	0	1	0	0	6	1	0	0	0	0	1	0	0	10
15	3	1	0	2	2	1	1	9	3	1	1	2	0	0	2	1	29
16	5	0	0	2	2	1	0	5	2	1	0	1	1	2	1	0	23
17	5	0	0	1	2	1	1	1	1	0	0	0	0	1	1	0	14
18	4	0	0	0	1	1	1	3	1	1	0	1	1	1	0	0	15
19	4	0	0	0	1	0	0	1	1	0	0	0	0	0	1	0	8
20	1	1	0	0	1	0	0	3	0	0	0	0	0	0	0	0	6
21	5	0	1	1	1	0	1	2	1	1	0	3	1	0	0	1	18
22	5	0	1	2	1	0	0	4	3	0	0	1	0	0	1	0	18
23	8	0	0	0	1	0	0	1	4	0	1	2	0	0	0	1	18
24	9	1	0	0	2	1	2	1	3	0	1	1	0	0	1	1	23
Total	158	19	6	20	45	23	40	74	34	19	14	38	23	17	30	17	577

Q15 Thinking more generally about alternative materials in construction, how important do you believe the following factors are in preventing their use?

		Not at all important	Somewhat unimportant	Somewhat important	Very important	Extremely important	Mean
1	High costs	1	0	3	15	13	4.22
2	Institutional culture and established practice	0	1	6	13	12	4.13
3	Insufficient design or performance information	0	2	3	16	11	4.13
4	Lack of design knowledge and skills	0	2	3	17	10	4.09
5	Shortage of skilled labour	0	5	11	12	4	3.47
6	Lack of regulation	0	7	11	5	9	3.50
7	Lack of demonstration projects	0	4	12	10	6	3.56
8	Time constraints	2	3	13	13	1	3.25
9	Bad press	2	5	16	6	3	3.09
10	Conservative nature of clients	0	0	8	15	9	4.03
11	Negative perceptions of industry	0	4	10	8	10	3.75
12	Other	0	0	2	0	4	4.33
13	Other	0	0	2	0	1	3.67

'Other' reasons noted were: lack of viable precedent, lack of comparative strength of most low carbon materials, good education/practical experience, do not have those materials available at local industry, energy costs are too low

Q16 How important do you believe the following developments could be in encouraging greater use of alternative materials and construction products?

		Not at all important	Somewhat unimportant	Somewhat important	Very important	Extremely important	Mean
1	Higher value in assessment schemes (e.g. BREEAM)	1	0	14	12	5	3.63
2	Regulation limiting embodied carbon in construction	0	1	3	13	15	4.31
3	Reductions in material cost	0	0	5	13	14	4.28
4	More environmentally conscious clients	0	0	8	9	15	4.22
5	More information on material performance and design	0	0	4	15	13	4.28
6	More demonstration projects and case studies	0	0	10	12	9	3.97
7	Training on designing with alternative materials	0	2	7	12	11	4.00
8	Other	0	0	0	0	1	5.00

'Other' reason noted was: sudden rise in energy costs

Appendix D - UK BIEC model development

This appendix contains additional detail on the development of the UK Buildings and Infrastructure Embodied Carbon model (UK BIEC) discussed in Chapter 5. The first section (D1) presents a summary of the decision-making process behind the model's key assumptions. The second section (D2) presents supplementary detail on the development of output profiles for non-domestic building classes within the model.

D1. Assumptions for UK BIEC model development

Owing to the limited availability of sector and project level carbon data, the model development required a number of assumptions. Once the principal model purpose was established, a set of outstanding questions concerning its implementation were collected. Potential responses to these questions were set out in a decisions matrix (overleaf). The alternate responses were assessed against four core criteria: accuracy, practicality, granularity and opportunity for further improvements. The decisions were discussed by the author with the supervisory team and made subject to review by an independent academic. An initial version of the model was also presented at the 2015 Lolo Sustainability and Buildings Conference, with the underlying assumptions open to review and discussion. The matrix overleaf sets out the questions and responses, with the preferred option highlighted in green. The four criteria are briefly outlined below.

Accuracy: Will the assumption significantly improve or reduce the accuracy of the approach in representing reality? Will the assumption substantially increase the uncertainty of the results?

Practicality: Is it practical to assemble sufficient initial data to implement the approach in a reasonable timeframe? Is it practical to manage the ongoing requirements of the approach as periodic updates are made to the model? Is it possible to implement the approach in an easily explicable manner with an acceptable degree of transparency? Can the model handle the volume of data required and still provide acceptable run times on a typical desktop computer?

Granularity: Will the approach significantly improve the number or representation of sub-sectors within the model? Will the approach provide sufficient granularity to allow modelling of plausible proposals (such as the introduction of regulated limits)? Will the approach offer new insights not apparent from already published benchmarks?

Opportunity for further improvements: Are there significant opportunities for the approach to improve in accuracy or granularity with the input of anticipated data gathering? Could the approach be easily refined or replaced within the model as additional information becomes available?

Model question Solutions considered	Accuracy	Practicality	Granularity	Opportunity
Building classes				
What building classes should the model include?				
The principal data sources (ONS output data, WRAP ECBD data, RICS benchmarks and WRAP RE benchmarks) are all categorised into different building classes.				
ONS Classes: New housing, Factories, Warehouses, Oil, steel and coal, Schools and universities, Health, Offices, Entertainment, Garages, Shops, Agriculture and Miscellaneous	Highest resolution of output data, but poor availability of detailed LCA data for many classes	Large number of classes to implement	Excessive degree of granularity as output for sectors such as oil, steel and coal represents less than 1% of annual new work	May be possible to gather detailed LCA data on classes such as garages and oil, steel and coal in future
9 Classes: Housing, Factories, Warehouses, Education, Health, Offices, Entertainment, Retail and Miscellaneous (These 9 are based on a concordance matrix between data sources – see Table 25.)	ONS data represents output of each class	Manageable number of classes	Reasonable for first model version. Each class represents 2-37% of overall output depending on year.	Sectors could be further disaggregated in future if more detailed data becomes available.
How should expenditure and emissions from the construction of infrastructure be represented in the model?				
Partially disaggregated by project type based on ONS data and assigned benchmarked carbon intensities, where data is available, with the remainder of expenditure deemed to have the same average carbon intensity	Improved accuracy with disaggregation but only where detailed LCA data exists. Assumption for remainder of expenditure may be invalid or skewed depending on data availability.	Poor data availability for many classes restricts the practicality of such an approach. It is likely that data would need to be taken from multiple sources.	Provides high degree of granularity.	Could be improved upon as more detailed LCA data becomes available.
Kept as separate class with emissions proportional to infrastructure output's share of total construction output	Dubious accuracy. Unlikely that infrastructure has the same carbon intensity as buildings.	Very simple to implement.	Provides no granularity. Effectively model becomes a buildings only model.	Could be disaggregated at a later date once better data becomes available.
Kept as separate class with emissions calculated based upon output and WRAP RE benchmarks	Places high dependence on accuracy of WRAP figures which are based on small sample size.	Simple to implement.	Provides no granularity.	Could be disaggregated at a later date once better data becomes available.

Model question Solutions considered	Accuracy	Practicality	Granularity	Opportunity
What should be done with building classes for which there are limited building level LCA studies?				
Assume carbon intensity of limited studies is typical	Subject to high degree of uncertainty and inaccuracy.	Very simple to implement.	Minimal granularity for modelling changes.	Will improve as more data becomes available.
Assume a carbon intensity function from a similar sector	Only accurate if sector closely mirrors output of similar sector.	This may not be possible for all sectors.	Potentially poor granularity for modelling changes.	Will improve somewhat as more data becomes available.
Insert an average carbon intensity or carbon intensity function based on a set of published benchmarks (i.e. RICS or WRAP RE benchmarks)	Places high dependence on benchmarks which are also based on small samples.	Easy to implement.	Potentially poor granularity for modelling changes.	Could be changed at a later date once better data becomes available.
Assign class a total carbon footprint with emissions proportional to class' share of total buildings output	Dubious accuracy. Assumes carbon intensity is the same for different building classes.	Simple to implement.	Poor granularity for modelling changes.	Could be disaggregated at a later date once better data becomes available.
How should 'miscellaneous' buildings that do not fall within a detailed class be represented in the model?				
Assign miscellaneous class a total carbon footprint with emissions proportional to class' share of total buildings output	Dubious accuracy. Assumes carbon intensity is the same for different building classes.	Simple to implement.	Poor granularity for modelling changes.	Unlikely to improve with time.
Assume miscellaneous carbon intensity function is similar to that which would be generated by combining data for all other classes	Dubious accuracy.	Challenging to implement.	High granularity for modelling changes.	May improve with further data.
Calculate total carbon footprint based on miscellaneous output multiplied by average carbon intensity from all other building classes	Dubious accuracy. Assumes carbon intensity is the same for different building classes.	Fairly simple to implement.	Poor granularity for modelling changes.	May improve with further data.
Calculate total carbon footprint based on miscellaneous output and WRAP RE benchmarks	Dubious accuracy. Places high dependence on accuracy of WRAP figures which are based on small samples.	Simple to implement.	Poor granularity for modelling changes.	Will not improve with time.

Model question Solutions considered	Accuracy	Practicality	Granularity	Opportunity
Data				
What is the best way to deal with inconsistencies in building LCA data sets? *The building level data sets suffer from differing system boundaries, reporting metrics, underlying LCA data sets, locations and assessment years.*				
Ignore these inconsistencies and use all available studies (removing extreme outliers where necessary).	Low degree of accuracy as using some incomparable data.	Simple to implement.	Provides highest granularity.	Will improve with time as more practitioners use common data sets and standards.
Limit studies to those that meet certain requirements (same LCI data sources, system boundaries and assessment year).	Higher degree of accuracy for individual data points. However, may lead to lower degree of overall accuracy owing to the reduction in the size of data sets used to generate carbon intensity functions.	Requires time consuming process of screening data. Also open to dispute about how requirements have been selected.	Reduces granularity, as may lead to insufficient sample for certain building classes.	Will improve as more data becomes available over time. However, may need to change limits over time also as better data sources emerge.
What functional unit shall be used for output of each building class? *Different functional units may be more appropriate (and are preferred in practice) for different building classes. However, comparing assessments across building classes would be easier with a common functional unit.*				
Use a common functional unit, such as Gross Floor Area (GFA) or Net Internal Area (NIA), across all building classes	Outputs may appear unfamiliar to practitioners and be of less practical use.	Simple to implement and comprehend.	No change.	Unit could be updated, or separate units introduced for each class, as more data becomes available.
Select an appropriate functional unit for each building class (from GFA, NIA, rental value, sales per unit area etc.)	Higher degree of accuracy but reduced comparability.	Harder to source variety of data and more complex to implement.	No change.	Results will improve as more data becomes available.

Model question Solutions considered	Accuracy	Practicality	Granularity	Opportunity
How should carbon intensity functions for each year be established?				
Calculate the carbon intensity function for each class based upon the building LCA studies from all available years. Assume this corresponds to the carbon intensity function for a single base year. Apply the same carbon intensity function to the total class output for each of the other years for which data is available.	Makes implicit and incorrect assumption that LCA figures and the shape of carbon intensity function has not changed over time. This will reduce accuracy.	Simple to implement. However, does require justification of base year selection.	Assumes same shape of carbon intensity function for all years.	Results will improve as more data becomes available. In future can be disaggregated to produce function for each year.
Calculate a carbon intensity function for each class for each year based upon the available building LCA studies from each year.	Very limited sample size means likely to be very inaccurate and distributions for some years may not be possible.	Not complicated to calculate but insufficiency of current data sets would prevent implementation.	Would provide higher degree of granularity that reflects different functions for each year.	Method could become feasible if sample sizes increased significantly as more data becomes available over the coming years.
When calibrating, should the model be adjusted for significant past changes in production technology? *Reductions in carbon intensity of key material manufacturing processes have been achieved over the calibration period. A significant proportion of these reductions is likely attributable to decarbonisation of the electricity grid and improvements in cement production facilities. There will be further changes in these factors over time.*				
Ignore influence of past changes	May reduce accuracy and inadvertently imply that past construction methods were more carbon intensive.	No additional effort.	No change.	Could be replaced with a more complex method at a later date.
Determine the proportional improvements in grid intensity and cement production in each year (or calculate the average over the period) of the calibration period and apply this improvement to carbon intensity functions for each year.	Could improve accuracy but would likely depend on accuracy of figures used to account for these changes. Difficult to justify inclusion and exclusion of particular technologies.	Complex to implement and requires additional data representing improvements.	No change.	Could be updated with more detailed data representing improvements or additional major changes if such data becomes available.

Model question Solutions considered	Accuracy	Practicality	Granularity	Opportunity
What time period should be used for calibration of the model?				
10 year period	Provides reasonable length of calibration period. However, this period spans an unprecedented recession that is unrepresentative of practice over recent decades.	Simple to implement.	No change.	Could be replaced with longer time period if confidence in accuracy of earlier data increases.
17 year period	Lower accuracy in data from earlier years. However, longer calibration period.	Simple to implement.	No change.	Could be improved if estimates from earlier years are refined.
Pre-recession or post-recession period only	Limits calibration period to a few years.	Simple to implement. Easier to calibrate against simple trend.	No change.	Will improve over time as data for future years becomes available.
Separate pre and post-recession periods	Probably most accurate means of calibration.	Significantly more complex to implement.	No change.	
What base year should be used for the analysis?				
2007 (peak annual construction output pre-recession)	Represents the sector near peak output. However, sector may take years to recover to this level, so may not be a fair reflection of current sector practice.	No significant difference in practicality between particular years.	No change.	Base year could be changed in future.
2013 (most recent year data is available for)	Most recent but still represents sector during a time of historically very low output.	No significant difference in practicality between particular years.	No change.	Base year could be changed in future.
Calculate and use the most common year that building level LCA data were generated in	Fairest representation and likely highest accuracy.	Slightly more complex to implement as need to compute most common year from evolving data set.	No change.	Base year could be updated as more building level data becomes available.
2011 (current most common entry in principal data source - WRAP Embodied Carbon Database)	Probably best representation at present but database will be updated over time.	No significant difference in practicality between particular years.	No change.	Base year could be changed in future.

Model question Solutions considered	Accuracy	Practicality	Granularity	Opportunity
2008 (central year for 10 year calibration period)	This year features both peak output and sharpest reduction in output due to effects of the recession. May result in greater inaccuracy.	No significant difference in practicality between particular years.	No change.	Base year could be changed in future.
2005 (central year for 17 year calibration period)	Nearly a decade ago. Accuracy of forward projections could be improved by using a year that more closely resembles current industry practice.	No significant difference in practicality between particular years.	No change.	Base year could be changed in future.
How will the distribution of building level LCAs be translated into a carbon intensity function representing the building footprints of projects of that class? *The output of each class must be represented by a carbon intensity function that relates output with carbon footprint. This must be based on a limited range of available building level LCAs and the total output of each class.*				
Assume that the sample of building footprints is representative for each class. Calculate the Gaussian probability density function that represents the distribution of building footprints for each class. Scale the resultant function by the output of each class.	Assumption that sample is representative is likely inaccurate. However, provides smooth curve representing plausible spread of carbon intensity. May be influenced by outliers, including smaller projects.	Simple to implement.	No change.	Results will improve as more data becomes available.
Assume that the sample of building footprints is representative for each class. Calculate each building's output as a proportion of the total sample output for each class. Plot these values against footprint and generate a function to fit this distribution. Apply this function to the total class output.	Assumption that sample is representative is likely inaccurate. Results would be dominated by larger buildings in the data set.	Involves additional simple layer of calculation.	No change.	Results will improve as more data becomes available.

Model question Solutions considered	Accuracy	Practicality	Granularity	Opportunity
What should be done with significant outliers in the buildings LCA database?				
Exclude significant outliers from analysis using simple criteria – e.g. number of standard deviations difference from rest of sample.	Will improve smoothness of carbon intensity functions but may not correctly represent real distribution of values.	Simple to implement.	No change.	Accuracy should improve as data set increases in size.
Include outliers provided that, upon inspection, LCA studies meet a set of basic requirements (such as incorporation of all major building elements, use of an up-to-date LCI source, location within the UK etc.)	Requires subjective decision about what basic requirements should be included.	More time consuming to implement as underlying data will require closer inspection.	No change.	Could update to incorporate stricter requirements as available data set increases in size.
Use a function generation method that gives minimal weight to outliers	Will improve accuracy.	More complex to implement.	No change.	Accuracy should improve as data set increases in size.
How should output data in financial terms be translated to physical units? *Footprint data is calculated in a physical unit. Output data is expressed in financial terms. Additional data is needed to replace elements or convert between these two units.*				
Convert all output data to physical terms using quoted or assumed prices	Highly dependent on accuracy of prices.	Simple to implement provided price data can be sourced.	No change.	Could be improved with refinements to price estimates.
Replace financial output with direct physical data where possible and convert remainder using prices.	Will only offer improvement in accuracy if significant data on physical outputs is included. Relies on more complex mixed methodology.	More effort to source data and implement on class specific basis.	No change.	Could be improved as more data representing physical outputs is sourced.
Use only footprint data reported in terms of financial value (i.e. $kgCO_2e$/£ output)	Ensures simple and consistent unit. However, severely limits the number of projects that can be used to generate carbon intensity functions. This may reduce overall accuracy.	Simple to implement.	No change.	Result should improve as more data becomes available.

Model question Solutions considered	Accuracy	Practicality	Granularity	Opportunity
How should differences in bottom up and top down emissions be resolved?				
Top down emissions from construction sector MRIO results will not match total bottom up emissions (total of carbon intensity functions multiplied by output). This is to be expected owing to the difference in system boundaries. The difference in these two data sets must be resolved if the full sector impacts are to be accurately distributed and addressed.				
Reallocate top down emissions to carbon intensity function of each class in proportion to the share of total output of each class. Apply this extra allocation as an x-shift in the carbon intensity function.	Inherent assumption in reallocated proportion that the carbon intensity of each class is the same per unit of output.	Relatively simple to implement. Easy to update with future output figures.	No change.	Minimal opportunity for improvement.
Reallocate top down emissions to carbon intensity function of each class based upon proportion of total bottom up emissions attributable to each class. Apply this extra allocation as an x-shift in the carbon intensity function.	Places greater reliance on the assumption that the bottom up data sample is representative and accurate.	More complex to implement.	No change.	Result should improve as more bottom up data becomes available.
Do not reallocate the difference but endeavour to retain consistent gap between top down and bottom up approaches over calibration period.	Requires subjective decision about base year and what size of gap to hold the difference to.	Complex to implement.	No change.	Likely to become more inaccurate over time as likely that the boundaries and accuracy of building level LCAs will improve over time. Consequently gap should be expected to decrease.

Model question Solutions considered	Accuracy	Practicality	Granularity	Opportunity
Output profiles				
What data or assumptions can be used to characterise past and current output profiles? *ONS output data represents the financial value of work in each class. However, it is also necessary to detail output in the selected functional unit.*				
Assemble outputs in functional unit for each class from multiple data sources. Where physical measures of output are not available, convert from financial value of output using prices.	Data will be of differing accuracy between classes.	Requires additional effort to attempt to source physical data for each class.	May offer reduced granularity if data for particular classes is not available.	Can be updated if additional information becomes available.
Convert financial value of output to functional unit using typical prices	Places high dependency on accuracy of prices.	Requires sourcing of prices. Easy to implement once table of prices assembled.	Retains granularity if price data for each class can be obtained.	Can be easily updated with revised prices.
What data or assumptions can be used to project future demand profiles?				
Use projections based on past trends in output for each class	Given the effects of the recession and current plans to invest heavily in infrastructure and housing, past trends may not be indicative of future output.	Requires assumptions be made about period over which to generate profiles. Relatively easy to implement after these assumptions are made.	Retains granularity.	Can be automatically updated based on additional output data each year.
Use independent projections from other sources e.g. Construction Product Association; Experian forecasts etc.	May be difficult to match classes to sectors used in projections produced by others. Projections may not cover desired analysis period.	Requires assembly of projections and selection between sources.	May have reduced granularity depending on ability to match classes to sectors used in projections.	Can be updated with revised projections as they become available.
Develop novel class specific projections from a range of sources – e.g. National Infrastructure Plan	Most subjective approach. Depends upon author assumptions and assumed interlinkages between key economic variables and class outputs.	Requires significant effort to gather data representing demand for each class.	Retaining granularity will depend on availability of class specific data.	Can be updated as more detailed data is added.

Table 25: Building classification concordance matrix

UK BIEC	ONS	WRAP ECBD	WRAP RE benchmarks	RICS benchmarks	
Housing	Housing	Residential	Residential & Houses 2, 3 & 4 bed	16 relevant entries	Villa, Detached Single Family Home, Semi Detached, Mid Terrace/Row House, End Terrace/Row House, Courtyard House, Townhouse - mid row, Townhouse - end row, Maisonettes 4 storey, Low Rise Apartment (3-5 storey building), Medium Rise Apartment/Condo (6-10 storey building), Medium Rise Apartment (11-15 storey building), High Rise Apartment/Condo (16-25 storey building), High Rise residential tower (16-25 storey building), High rise tower (residential 26+ storey building), Communal dwelling (nursing home, hall of residence)
Factories	Factories	Factories	Industrial	3 relevant entries	Small - medium light industrial, Large light industrial/factory units, Multistorey factory complex
Warehouses	Warehouses	Warehouses		Warehousing/ logistics	
Included in Miscellaneous	Oil, steel and coal				
Education	Schools and universities	Educational	Education	2 relevant entries	University/Higher/Further education, Primary school/kindergarten/nursery
Health	Health	Healthcare	Health	3 relevant entries	Hospital (general, acute, teaching, specialist), Hospital (community, mental health), Health centre/surgery
Offices	Offices	Offices	Office	4 relevant entries	Low Rise Offices (1-4 storey building), Medium Rise Office Block (5-10 storey building), Medium Rise Office Block (11-15 storey building), High Rise Office Block (16-25 storey building)
Entertainment	Entertainment	Recreational		6 relevant entries	Bars, Leisure park (Cinema, bowling, restaurant, amusements), Sports/leisure centre (no swimming pool), Swimming pool centre, Leisure complex including swimming pool, Specialist leisure (stadia, arena, other sports facilities)
Included in Miscellaneous	Garages				
Retail	Shops	Retail	Retail	3 relevant entries	Retail mall/shopping centre, High street retail/district centre, Food and beverage retail (restaurants, cafes)
Included in Miscellaneous	Agriculture				
Included in Miscellaneous	Miscellaneous				

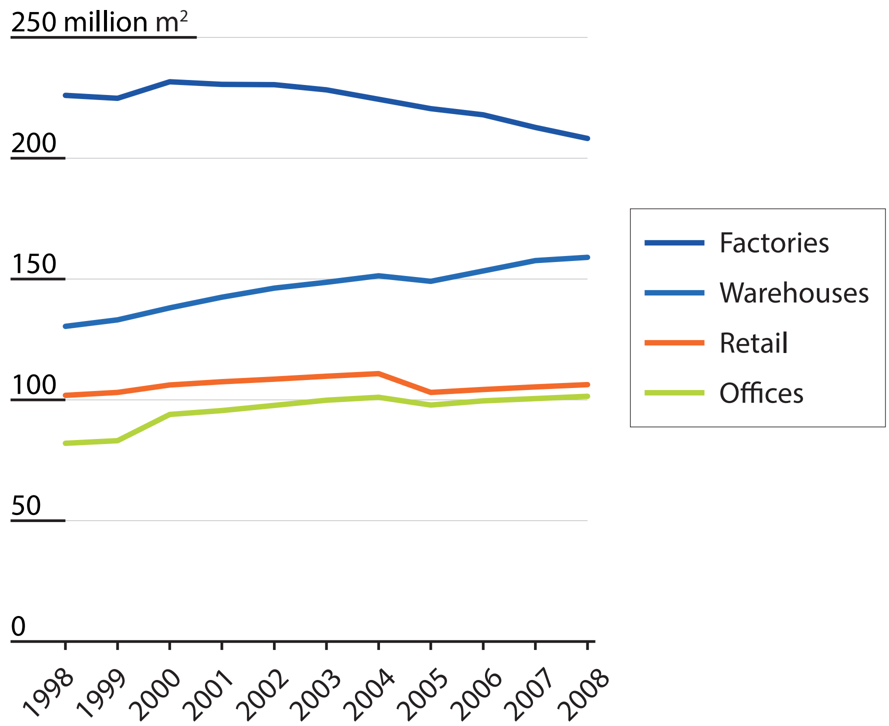
D2. Calculation of output profiles for UK BIEC non-domestic building classes

This section details the development of output profiles for non-domestic building classes used within the UK BIEC model presented in Chapter 6. Output profiles were computed from a combination of financial value of output (ONS 2015) and historic price data obtained from numerous editions of the Spon's Architects' and Builders' Price Book (AECOM 2015). Where required, the mix of properties of each class are assumed to correspond to the proportions observed by Bruhns et al. (2000). The specific price data used for each class are presented below, with all output profiles compared with the VOA estimates of non-domestic stock (see Figure 45). The estimated output of all non-domestic classes is shown in Figure 25.

Factories

VOA floorspace data for factories from 1998-2008 varied between a peak of 231,579,000m^2 in 2000 and a low of 208,171,000m^2 in 2008. The decline over this period is likely due to the long term decline of the UK manufacturing sector. Annual changes in stock of 2-4 million m^2 were typical, suggesting a turnover exceeding 1-2% of stock per year. In Spon's a variety of prices are quoted for factories depending on size, ownership, facilities and use. The most common was assumed to be 'Factories for letting (including lighting, power and heating)'. Central price estimates for this class were used alongside ONS new work data to establish new build floor areas. The resulting estimate ranges between 3-7 million m^2 per annum.

Figure 45: VOA estimates of UK non-domestic building stock 1998-2008



Warehouses

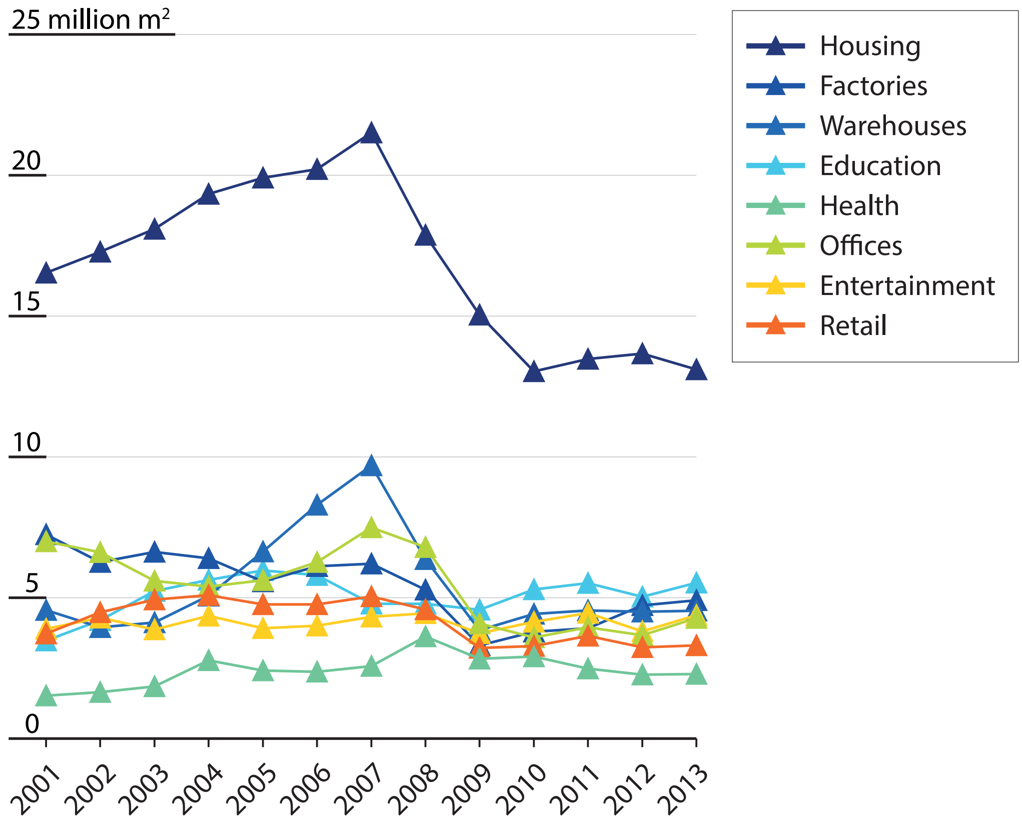
VOA floorspace data for warehouses indicates a largely uninterrupted expansion in stock from 130,333,000m^2 in 1998 to 158,942,000m^2 by 2008. During this period stock grew at a rate of 2-4 million m^2 per year. ONS new work data for warehouses confirms this rapid expansion of warehouse production until 2007, followed by a dramatic decline brought on by the recession (see Figure 25). This expansion in warehousing also coincided with a substantial increase in the typical size of warehouses. This is reflected in the changing classification of warehouses in the Spon's price books. For example, the 1998 edition includes warehouse classifications of:

- Low bay (6-8m high) for letting (no heating)
- Low bay for owner occupation (including heatin
- High bay (9-18m high) for owner occupation (including heating)

In comparison the 2015 edition classifies warehouses as:

- High bay (10-15m high) for owner occupation (no heating) up to 10,000m^2
- High bay (10-15m high) for owner occupation (no heating) over 10,000m^2 up to 20,000m^2
- High bay (16-24m high) for owner occupation (no heating) over 10,000m^2 up to 20,000m^2
- High bay (16-24m high) for owner occupation (no heating) over 20,000m^2

Figure 25: Estimated annual new build floor areas by building class 2001-2013



To account for the changing size of warehouses during this period, a mix of classifications were used to form an average price for each year. It has been assumed that a gradual shift occurred from predominantly low bay to increasingly large high bay warehouses over the analysis period. This gives an estimate of 3-9 million m^2 per year, which broadly agrees with the increases observed in the VOA data.

Offices

VOA statistics for office floorspace suggest that total stock grew from 82,011,000m^2 in 1998 to 101,456,000m^2 in 2008. Spon's prices were available for a wide variety of office types. 'Medium rise, air conditioned' was selected as the most representative, with an equal split between 'offices for owner occupation' and 'offices for letting'. Around half of all UK office space is rented, with the remainder owner occupied, and these proportions have remained stable over the last decade (The Association of Real Estate Funds et al. 2014 p. 6). Combining price data with ONS new work data gives estimated annual new build floor areas of 5-8 million m^2 per year.

Retail

VOA statistics for retail floorspace suggest that total stock fluctuated between 101,827,000m^2 and 110,840,000m^2 between 1998 and 2008. The majority of this stock is composed of small or medium sized shops with the Bruhns estimates suggesting only around 18% of retail floorspace is large stores or supermarkets. A typical price was therefore calculated from a mix of small (82%) and large (18%) 'shop shells including fitting out'. Combining price data with ONS new work data gives estimated new build floor areas of 3-5 million m^2 per year.

Education

It can be concluded from the Bruhns estimates of the existing educational building stock that the combined floor area of schools is comfortably greater than the combined floor area of all other educational building types (universities, colleges etc.). For this reason prices for 'Secondary/middle schools' were taken as representative of all spending on educational buildings. Updating the Bruhns estimates to current stock would suggest an educational stock in the region of 100 million m^2. Combining price data with ONS new work data gives an estimate of new build annual floor area of 3-6 million m^2 per year.

Health

It is also clear from the Bruhns estimates of the existing stock that the combined floor area of hospitals constitutes the overwhelming majority of buildings serving as healthcare facilities. For this reason prices for 'District hospitals' were taken as representative of all health spending. The Bruhns estimates suggest a stock in the region of 30 million m^2. Combining price data with ONS new work data gives an estimate of new build floors areas between 1-4 million m^2 per year.

Entertainment

Entertainment expenditure is distributed across a wide variety of building types, e.g. art galleries, sports facilities, theatres, night clubs and casinos. Consequently establishing a typical price for entertainment buildings is difficult. The Bruhns stock estimates suggest that of the 68 million m^2 of buildings of this nature, the most common are pubs (33% of total) and hotels (28%). The remainder could be broadly grouped into: sports facilities (16%); restaurants, cafes and takeaways (8%); theatres and cinemas (2%); and museums and art galleries (2%); with a diverse range of structures making up the remaining 11%. A combination of prices representing 'public houses', 'hotels' and 'health and fitness clubs' was used alongside ONS new work data resulting in annual estimates of new build floor area of 3-5 million m^2 per year.