Embodied Carbon Assessment and Decision Making Under Uncertainty:

Case studies of UK supermarket construction

Doctor of Engineering

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DECLARATION

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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Abstract

Estimates of the embodied carbon of buildings are resource intensive to produce and are subject to a wide range of uncertainties. Much of the time spent conducting an assessment is allocated to collate quantities of materials. Carbon factor data are a further important input to the assessment. A range of possible sources of carbon factors are available and these display high variability both in magnitude for a given material and also in terms of data quality. These features impair the use of such assessments in attempts to reduce carbon emissions associated with buildings.

This research presents a simpler means of producing embodied carbon estimates and assesses the impact of uncertainty to improve decision making about carbon reduction, in the specific case of supermarket buildings. This approach is applied to a number of case studies of buildings constructed by Sainsbury's Supermarkets Ltd. in the UK.

A new approach has been developed for estimating embodied carbon using Building Information Modelling as a source of material quantity data. The approach demonstrates how establishing a machine-readable link between this data and carbon factor data, for example from Environmental Product Declarations (EPDs) facilitates semi-automation of an important step in the assessment process. In comparison to more traditional, manual methods, this new method offers improved efficiency by reducing repetition of data entry.

The thesis also examines the possible effects of uncertainty and the analysis has shown that despite recent efforts to increase standardisation of EPDs across Europe, significant uncertainties remain. An approach recently applied in related fields of environmental assessment, which combines qualitative and quantitative assessment techniques, is used to show how these effects may be better understood and mitigated. The value of this approach is demonstrated by applying it to the results of comparative embodied carbon assessments of the kind that might typically be used to support the design of low carbon buildings.

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List of Publications

Conference papers

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Others

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Abbreviations

BIM	Building information modelling
BOF	Basic oxygen furnace
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DOCf	Degradable organic carbon fraction
EAF	Electric arc furnace
ELCD	European Life Cycle Database
EPD	Environmental product declaration
GGBS	Ground granulated blast-furnace slag
GHG	Greenhouse gas
GWP	Global warning potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
OHF	Open hearth furnace
OPC	Ordinary Portland Cement
OSB	Oriented strand board
PFA	Pulverised fly ash
PU	Polyurethane
RC	Recycled content
RMC	Ready mixed concrete
SCM	Supplementary cementitious material
SE	System expansion

1 Introduction

1.1 Carbon Abatement in the Built Environment

Buildings are a key focus of the global effort to tackle climate change because they offer 'the most potential for delivering significant and cost-effective GHG [green-house gas] emission reductions' (United Nations Environment Programme, 2009, p. 4). A requirement to limit carbon emissions from new buildings was introduced into UK Building Regulations in 2006 to supplement the existing minimum thermal insulation standards (Hamza & Greenwood, 2009). To date, Building Regulation Part L (Department for Communities and Local Government, 2016) focuses on *Conservation of Fuel and Power* use during building operation. Carbon emissions arising from the production of raw materials, transport and construction activities, maintenance and subsequent demolition and disposal, collectively termed embodied carbon, are not currently directly regulated under UK law.

Early research on embodied carbon of buildings suggested its contribution was small relative compared to operational carbon emissions, which were found to contribute around 90% to the whole life cycle carbon of sample buildings assessed (Scheuer et al., 2003; Buchanan & Honey, 1994; Oka et al., 1993). Recent research based on UK construction data suggests that for buildings constructed after 2006, embodied carbon can range from 15% - 50% of the total carbon emissions depending on the building type (Darby, 2014, p. 270 Fig 7-4). Policies to reduce operational carbon have contributed to this increase in the relative significance of embodied carbon. A report by the Green Construction Board (2013) showed that, in order for the UK construction sector to achieve its 80% emissions reduction goal, in line with the UK Climate Change Act (2008), both operational carbon and embodied carbon of buildings need to be significantly reduced.

The term carbon is widely used as shorthand for all greenhouse gas emissions. This stems from the practice of comparing the global warming potential of different greenhouse gases to that of carbon dioxide (CO_2) using the measurement unit of carbon dioxide equivalent (CO_2e). In many cases the term carbon also implicitly refers specifically to those greenhouse gas emissions caused by human activity. Natural greenhouse gas emissions combined with natural carbon sequestration form the Earth's carbon cycle and the quantities released and absorbed far outweigh emissions from human activity (IPCC, 2007 Fig. 7.4). But in terms of climate change, it is this relatively small contribution of emissions from human activity which upsets the cycle. In this thesis, the term carbon is used in preference over more precise, but rather unwieldy alternatives such as anthropogenic greenhouse gas emissions. Where a distinction is being made between greenhouse gas emissions generally and carbon dioxide emissions specifically, the abbreviations CO_2e and CO_2 are used respectively.

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1.2 Sainsbury’s Motivation to Address Embodied Carbon

1.2.1 Background

Sainsbury’s is the UK’s second largest supermarket business (Kantar Worldpanel, 2016) and has an estate of over 1200 stores, comprising more than 500 large supermarkets (typically above 25,000 ft^2 sales area) and 700 smaller convenience stores (typically around 3000ft^2), (J Sainsbury plc, 2017). In 2011, Sainsbury’s launched a sustainability plan with 20 commitments to be achieved by 2020. The plan included ambitious targets for operational carbon reduction. By 2020 operational emissions are to be reduced by 30% in absolute terms compared to a 2005/06 baseline (J Sainsbury plc, 2011). The business has made some progress towards this target and by 2016, despite increasing total sales area by more than 50%, operational carbon was 0.3% lower than in 2005/06 (J Sainsbury plc, 2016a). Whilst there are commercial benefits to reducing operational carbon, primarily in the form of reduced energy costs, the business also has stated its commitment to supporting efforts to ‘limit the average global surface temperature increase to two degrees centigrade, a figure that the evidence suggests will help mitigate climate change’ (J Sainsbury plc, 2016b). In light of this commitment, the business recognized it needed to understand the impacts of embodied carbon in building construction and maintenance as well as along its supply chain, and to work towards incorporating targets for reducing embodied carbon into future sustainability planning.

1.2.2 Sainsbury’s Early Work on Embodied Carbon

Between 2007 and 2011 Sainsbury’s commissioned a number of studies to assess the life cycle (embodied and operational) carbon emissions of some of its new build supermarkets. This early work suggested that embodied carbon may be a significant contributor to building-related emissions. The results showed embodied carbon to be between around 10 and 40% of a new supermarket’s total life cycle carbon (Deloitte, 2010). A report published during this time by the Royal Institute of Chartered

Surveyors presented similar results and also suggested that embodied carbon of supermarket buildings could exceed operational carbon over the building life cycle, once UK legislation for buildings to be zero carbon in operation came into force (RICS, 2012a). Thus there appeared to be a strong case for Sainsbury's and other retailers to develop strategies and targets to reduce embodied carbon of supermarket buildings.

A research partnership with Reading University's TSBE Centre was established to further investigate embodied carbon, its impact and implications in the context of UK supermarket construction, and to establish appropriate quantitative assessment methods. This doctoral thesis is the culmination of the research work undertaken.

1.3 Embodied Carbon Assessment

Embodied carbon of buildings can be defined as "the CO_2 or GHG [greenhouse gas] emission associated with extraction, manufacturing, transporting, installing, maintaining and disposing of construction materials and products" (Anderson & Thornback, 2012). Embodied carbon assessments of buildings draw on principles and methods from the field of life cycle assessment (LCA) to quantify the combined carbon emissions of each of these life cycle stages.

Where LCA assesses multiple environmental impacts across the full life cycle, an embodied carbon assessment focuses on a single impact category (global warming potential, typically measured in terms of carbon emissions) and applies a reduced scope, omitting the operational carbon. Furthermore, because of the complexity of buildings and the range and extent of materials used, it is common to rely on secondary rather than primary data for the carbon emissions for each key material (G. Treloar et al., 2000; Fossdal & Edvardsen, 1995). These secondary data or carbon factors are available from a range of different sources which are discussed in more detail in the literature review in Chapter 2.

A number of possible sources of data for material and energy flows may be used. Prior to construction, material quantities may be obtained from design documentation such as drawings, digital models and bills of quantities. For assessments conducted post-completion, such data may be supplemented with data from order and delivery records. Building information modelling (BIM) has been identified by some as an opportunity to more readily produce inventories of building material inputs and outputs (Monteiro & Poças Martins, 2013; Basbagill et al., 2013; Schlueter & Thesseling, 2009). A digital design produced using BIM has information, in the form of meta-data, linked to each element or object of the model. For example, a wall in the model may have data attached which defines its material composition, its thermal performance and the material supplier. Since each object can be defined by its material and its supplier, it is possible to envisage how material quantities from a BIM model could also have carbon factors assigned to them for the purpose of estimating the embodied carbon of the building.

Sainsbury's has invested in the use of BIM for the design and construction of its new supermarkets. The possibility that BIM could be used to facilitate embodied carbon assessments was explicitly identified by the business as a potential benefit of the investment. An important requirement of the research undertaken with the University of Reading TSBE Centre is to identify and evaluate the options for achieving BIM-based embodied carbon assessments and to understand the implications of exploiting such capability for Sainsbury's existing BIM design processes.

1.4 Limitations of Embodied Carbon Assessment

Embodied carbon assessment is subject to theoretical, methodological and practical limitations, examples of these include:

Theoretical:

- Emissions associated with a particular material or product may occur at different times; often decades and possibly even centuries apart.
- Emissions of all greenhouse gases must be converted into a common metric to allow comparison.

Methodological and practical:

- Production processes are complex and subject to many variations including sources of raw material, production volumes, batching and so forth. Data are therefore often based on averages.
- Many production processes result in two or more co-products and emissions from the process must then be assigned to each product in some meaningful way to avoid double counting.
- Unless the assessment is conducted retrospectively, at the end of the building life cycle, assumptions must be made about future life cycle stages in order to account for all relevant emissions.
- Data collection can be very resource intensive, meaning simplifications may be necessary such as the use of secondary and proxy data or estimates; the exclusion from the study of certain parts of the building, or stages in the building life cycle; and the use of cut-off criteria to exclude those materials or processes deemed to contribute less than a specified threshold value.
- The opportunity to reduce embodied carbon is greatest in the early stages of design when the precise nature and quantum of different material inputs are uncertain.

A more detailed, qualified discussion of these limitations is provided in the literature review in Chapter 2. Different studies deal with these limitations in different ways, which has led to the variability in results from different assessments of embodied carbon in buildings (Moncaster & Song, 2012; Dixit et al., 2010) (See also section 2.3.3).

The existence of these limitations and the variability in results from different assessments of embodied carbon in buildings (Dixit et al., 2010), lead to the conclusion that the embodied carbon of a building cannot be known with complete certainty. And yet it is still desirable to use the results of embodied carbon assessments to inform design choices that might result in reductions in embodied carbon. The assessment and management of uncertainty is a well-established field of research (Ascough II et al., 2008) and the use of uncertainty assessment methods in LCA, whilst not universal, has become more commonplace in recent years (Heijungs & Huijbregts, 2004). The ISO 14040 series of standards for LCA specifically make reference to uncertainty. An uncertainty assessment is mandatory if an LCA study of a product is to be published with the intention of making comparative assertions about its environmental impacts (British Standards Institution, 2006a).

By contrast, the more recently published EN 15978 and 15804, which are specifically aimed at LCA of construction products and buildings, make no reference to uncertainty or uncertainty assessment (British Standards Institution, 2011a, 2014a). This omission is surprising, given that these standards are closely aligned with the older ISO 14040 standards. But given that uncertainty is ignored in both sets of standards, it is perhaps unsurprising, that uncertainty has been largely overlooked in much of the extant research on embodied carbon of buildings. For example, from a sample of 20 peer reviewed journal papers presenting embodied or life cycle carbon or assessments of buildings or construction materials, only five were found to include a detailed uncertainty assessment.

Those five were published relatively recently (Kua & Wong, 2012; Nässén et al., 2012; A. A. Acquaye, Duffy, & Basu, 2011; A. Acquaye, Duffy, & Basu, 2011; Gustavsson & Joelsson, 2010) and, together with references to uncertainty assessment in recent review and conference papers (e.g. Cousins-Jenvey et al., 2014; Ibn-Mohammed et al., 2013) suggests a possible growing awareness of the need for uncertainty assessment. Further evidence is available from the proceedings of the first Embodied Carbon and Energy Symposium hosted by Cambridge University Built Environment Sustainability group (CUBES) in April 2016. Risk and Uncertainty was one of six themes addressed in a series of focus groups held during the event. Participants in that discussion expressed the view that whilst uncertainty assessment, is viewed with some ‘scepticism from the industry,’ there is nevertheless ‘a profound link between uncertainty and decision making, and a better frame of reference for the former would certainly facilitate the latter.’ (Moncaster & Pomponi, 2016, p. 3)

There is a clear need to better understand the impact of uncertainty on embodied carbon assessments and the role that this plays when such assessments are used to inform decisions intended to reduce embodied carbon.

1.5 Research Aim and Objectives

There is a desire within Sainsbury's to understand and reduce the embodied carbon of supermarket buildings. The quantitative assessment of embodied carbon during the design of buildings represents an established method for achieving this. However, the collation of data is time and resource intensive and the various limitations of the method lead to considerable uncertainty about the results. The aim of this research is:

> **To propose and demonstrate a new approach to estimating embodied carbon of supermarket buildings during the design stage, taking account of uncertainty and evaluating how the approach may support decisions aimed at reducing embodied carbon emissions in construction.**

Objectives:

1. Identify suitable sources of data for use in the estimation of embodied carbon in supermarket construction and evaluate their usefulness for Sainsbury's.
2. Evaluate the potential to automatically generate material quantities data that are appropriate for embodied carbon assessments using Sainsbury's BIM models, and to make recommendations for their improvement.
3. Develop and demonstrate a new approach for estimating embodied carbon of supermarket construction on the basis of 1 and 2 above.
4. Investigate the nature and potential impact of uncertainty in estimating embodied carbon, and evaluate current approaches for assessing it.
5. Develop and demonstrate an approach to incorporating uncertainty assessment into the estimation of embodied carbon at 3 above to show the effect uncertainty can have on design decisions to reduce embodied carbon.
6. Examine how embodied carbon assessment results produced using this new approach can support Sainsbury's aim of reducing its climate change impacts.

1.6 Structure of the Thesis

The remainder of the thesis comprises six further chapters as follows:

Chapter 2: Presents a review of literature relating to embodied carbon assessment methods, limitations and sources of data. This is followed by a review of relevant literature on uncertainty and uncertainty assessment methods.

Chapter 3: Describes and justifies the research design and methods chosen to fulfil the research objectives.

Chapter 4: Presents a detailed description of the prototype calculation tool developed for design stage embodied carbon assessment. The mechanisms for extracting material quantities from BIM models are described and the limitations of this approach are investigated. Embodied carbon results generated from three case study supermarket designs are also presented and discussed. (Objectives 1-3)

Chapter 5: The uncertainty assessment methods selected for this research are presented. An uncertainty typology is used to categorise the key sources of uncertainty relevant to embodied carbon assessments. A method for assessing uncertainty in the embodied carbon factors of materials combining expert elicitation and scenario analysis is detailed. The chapter provides detailed descriptions of the criteria for selection of experts and the elicitation techniques used. (Objective 4)

Chapter 6: The results of the expert elicitations are presented and analysed. The first set of results is an evaluation of the data quality of different sources of carbon factors. This informs the selection of carbon factors for all the assessments conducted in the course of the research. The chapter then goes on to describe the development and implementation of scenarios to evaluate uncertainty in the embodied carbon factors of eight materials commonly used in supermarket construction. The scenarios are based on the outcomes of the expert elicitations. (Objective 4 and 5)

Chapter 7: Using the results of the scenario analysis presented in Chapter 6, three case studies are then modelled to demonstrate the possible effects of uncertainty on comparative embodied carbon assessments or material alternatives. (Objective 5)

Chapter 8: A critical analysis and evaluation of the results from the preceding chapters is given in chapter 8. The first part of the chapter discusses the outcomes of the first set of case studies. This discussion is framed by the outcomes of a recent review of embodied carbon mitigation strategies (Pomponi, D'Amico, & Moncaster, 2017). These strategies and their applicability for Sainsbury's and supermarket construction in general are evaluated in light of the results of the analyses in chapter 4. The potential and limitations of the approach to integrate BIM and embodied carbon are also critically reviewed. The chapter concludes with a discussion of the implications of the uncertainty assessment results for Sainsbury's design decisions and for the wider field of embodied carbon research. (Objective 6)

Chapter 9: Presents a summary of the outcomes, conclusions and recommendations of the research.

2 Embodied Carbon Assessment of buildings: A Literature Review.

The review of literature begins with an overview of recent work on embodied carbon, assessing general themes and methodological developments and providing a summary of outcomes. The focus then moves to BIM, and specifically, efforts to integrate this with various forms of environmental assessment methods, sometimes known as 'Green-BIM'. Work relating to uncertainty in embodied carbon assessments is presented and discussed including a systematic review of the use of uncertainty assessment methods in embodied carbon assessments and LCA of buildings and construction products.

2.1 Embodied Carbon Assessment Methods

Embodied carbon assessment draws on techniques and methods developed in the field of LCA. LCA is a quantitative approach to describing and managing the environmental impacts of a product (or sometimes a service) across its entire life cycle. The life cycle is usually defined from 'cradle-to-grave' (British Standards Institution, 2006a, p. v) and begins with the acquisition of raw materials (cradle), and ends with the final disposal (grave). It encompasses all stages of manufacture and processing to make the product; any transportation of goods; the use of the product, including maintenance and repair; and any processing required at the end of the product's useful life. Together, these different parts of the life cycle are known as the 'product system' (British Standards Institution, 2006a, p. 2).

Whilst LCA addresses multiple environmental impacts, life cycle carbon assessments or embodied carbon assessments only evaluate the global warming potential (GWP) of a product system. This focus on GWP or carbon may be due in part to the emphasis on carbon emissions in environmental legislation (Laurent, Olsen, & Hauschild, 2012), particularly in the UK buildings sector (King, 2007). GWP is driven by emissions of greenhouse gases (GHGs) due to human activity. GHGs include water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs); and sulphur hexafluoride (SF_6). The most important of these, in terms of the amount released to the atmosphere by human activity, is carbon dioxide, and the GWP of all other greenhouse gases is measured relative to CO_2, using the unit of carbon dioxide equivalent or CO_2e. Hence the terms carbon footprint and carbon emissions have generally come to mean all GHG emissions. Distinction between operational and embodied carbon is made within the building sector because of a historical focus in the UK and elsewhere on operational energy and carbon emissions, particularly in policy measures (Rai et al., 2011). For example the UK building regulations stipulate requirements for the energy performance and carbon emissions of buildings in operation, but do not currently regulate energy and carbon emissions from other parts of the lifecycle (Department for Communities and Local Government, 2016). Figure 2-1 illustrates how embodied carbon assessment fits into the broader field of LCA.

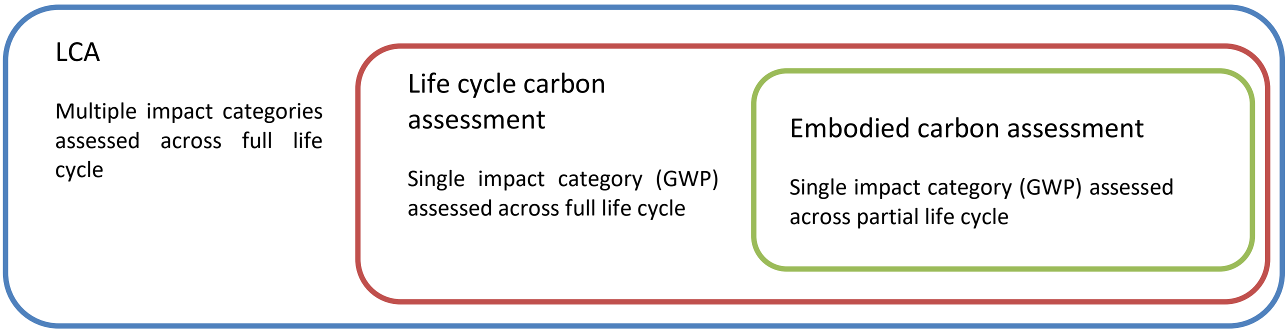

Figure 2-1: How embodied carbon assessment fits into the wider scheme of LCA

There are three main methods for conducting LCA and examples of all three methods applied to embodied carbon or life cycle carbon assessment of buildings have been found in the literature. The three methods are:

- Process analysis
- Environmentally extended input-output analysis (EEIO)
- A hybrid of process analysis and EEIO

2.1.1 Process Analysis

Process analysis “is a bottom-up method, which has been developed to understand the environmental impacts of individual products”(Wiedmann & Minx, 2007, p. 5). The method involves defining a product system with a system boundary and creating an inventory of all the inputs and outputs between that product system and the environment. These flows can be materials or energy, and once the inventory has been established, the environmental impact of each item in the inventory is evaluated. This method forms the basis of traditional LCA as described in the international standards ISO 14040 and 14044 (British Standards Institution, 2006b, 2006a).

2.1.2 Environmentally Extended Input-Output analysis

EEIO is a top down approach, in that it uses macro-economic data (national or regional input-output tables) as the basis for assessing the environmental impact of a product. Input-output tables ‘summarise economic transactions between sectors of an economy’ (G. J. Treloar et al., 2000, p. 7). A matrix operation known as the Leontief inverse, after Wassily Leontief who developed the method, allows the economic output from each sector to be evaluated in terms of all the necessary economic inputs from every other sector (Miller & Blair, 2009). By assigning environmental impacts such as carbon emissions to the economic flows from each sector, it is possible to estimate the total impacts of an output from any given sector.

EEIO methods are most suitable for high level assessment such as when considering emissions at a sector or national level (Murray & Wood, 2010; Crawford, 2005). The reason for this is that economic input-output (IO) data is highly aggregated. UK IO tables, for example, list construction as a single aggregated sector. Similarly, 'Fabricated metal products, excl. machinery and equipment and weapons & ammunition' is another aggregated category with no discrimination between different types of metal (ONS, 2013). This aggregation is reflected in EEIO models. For example, the Global Trade Assessment Programme (GTAP) EEIO model discriminates between 57 economic sectors and the World Input Output Database (WIOD) project comprises 35 industries and 59 product categories (Dawkins et al., 2011).

2.1.3 Hybrid Analysis

EEIO alone does not provide the level of detail required to discriminate between the impacts of individual products or components (Omar et al., 2014). Where EEIO has been applied to individual buildings, this is commonly in the form of a hybrid assessment which combines data from EEIO models with data from process analysis (Omar et al., 2014; G. J. Treloar et al., 2000). However, recent research has called into question the accuracy of hybrid assessment methods, suggesting that the high levels of aggregation in EEIO models may lead to significant overestimation of results (Yang, Heijungs, & Brandão, 2017).

Of the three methods, process analysis was found to be most commonly applied to conduct either LCA or embodied carbon assessments of individual buildings. This may reflect the fact that this is the method adopted in LCA standards and the data and tools to conduct process analysis of buildings are more widely available than for EEIO or hybrid analysis (For example, see Table 2 in Moncaster & Song, 2012).

2.2 Limitations of the LCA Method

2.2.1 Geographical and Temporal Limitations

Finnveden et al. (2009) describe how LCA modelling takes no account of the characteristics of the source of an emission and the environment into which it is emitted. For this reason, the results of LCA are always expressed as potential environmental impacts and cannot, in isolation, provide conclusive information on how the emissions from the product system will interact with the environment. The authors point out that for truly global impact categories like climate change, this is not a problem since the impact is independent of where the emission occurs. Yet the rate of radiative forcing, the mechanism responsible for global warming, is dependent on atmospheric concentrations of GHGs. Thus GHG emissions calculated using LCA are considered to have global warming *potential*. The results of an LCA or an embodied carbon assessment are not an indication of how much global average temperatures will rise as a result of those emissions.

2.2.2 System Boundary Limitations

The complexity of product systems necessarily requires analytical simplification through the drawing of system boundaries (Wiedmann & Minx, 2007). The system boundary may exclude elements of the product system whose inclusion is deemed unnecessary to meet the desired aim or goal of the assessment. The drawing of boundaries also usually includes the application of cut-off criteria (British Standards Institution, 2006a). This allows for material or energy flows, deemed to be below a threshold, to be ignored. This approach is criticized on the basis that it can lead to significant incompleteness (Treloar, 1997). In previous LCA and embodied carbon assessments of buildings, system boundaries have been set in such a way as to exclude certain phases of the life cycle either due to lack of data (Hammond & Jones, 2008) or because they are considered insignificant (Kofoworola & Gheewala, 2009).

2.2.3 Data Availability and Data Quality Issues

LCA and embodied carbon assessment requires data on system inputs and outputs to be gathered from primary or secondary sources. The availability and quality of that data 'is of core interest for LCA applicability' (Bretz, 1998, p. 121). Gathering primary data is a resource intensive process and requires access to suitable sources. Secondary data may be more readily available, but may not be fully representative of the process or material being assessed. In some cases, secondary data for the desired parameter may not be available and then a proxy may be required. A proxy is a parameter which is considered analogous or comparable to the desired parameter (Funtowicz & Ravetz, 1990). Some proxy data may be very closely correlated to the desired parameter, whilst in other cases, the link may be less clear (Risbey, Sluijs, & Ravetz, 2006).

Primary, secondary and proxy data may all have varying levels of data quality. In addition to the need for reliable data, Weidema and Wesnaes (1996) identify statistical, temporal, geographical and technological representativeness as being key factors affecting the quality of data regardless of its source. Statistical representativeness is determined by considerations such as 'the number of measurements in the sample and time periods for data collection' (Weidema & Wesnæs, 1996, p. 168). Temporal correlation refers to the age of data, since older data may not be representative of current methods or efficiencies. Geographical correlation can affect data quality since production processes may vary between countries or regions. Technological correlation is the consideration of how closely the technology upon which data are based correlate or represent the process or material that is being assessed in the study. The authors further define reliability to be related to appropriate sampling or measurement methods.

2.3 LCA and Embodied Carbon Assessments of Buildings

Despite the limitations described above, proponents of these LCA methods and their derivatives, such as embodied carbon assessments, point to the fact that there are few alternatives for assessing environmental performance (Finnveden, 2000) 'in a reliable and transparent way' (Baitz et al., 2013, p. 7). There is strong consensus in the literature that LCA techniques can be usefully and appropriately applied to assess the environmental sustainability of buildings and the built environment (Erlandsson and Borg, 2003; Ortiz et al., 2009). Khasreen et al. find that LCA techniques have been widely applied to buildings since the 1990s. Yet they also concede that methods are 'less developed than in other industries' (2009, p. 677). This has been attributed to a combination of factors including:

- the complexity of buildings – in terms of the number of products and materials they comprise (Moncaster & Song, 2012; Khasreen, Banfill, & Menzies, 2009),
- the long length of building life cycles and the complexity within the life cycle – in terms of maintenance regimes, refurbishments, changes of use etc. (Khasreen, Banfill, & Menzies, 2009; Erlandsson & Borg, 2003)
- the uniqueness of buildings as one-off products (Khasreen, Banfill, & Menzies, 2009; Moncaster & Song, 2012).

2.3.1 Building Level Assessments

In early examples of LCA of buildings, the focus was often on energy use. Life cycle or embodied energy analyses are closely related to life cycle and embodied carbon assessments using comparable techniques. Gonzales and Navarro (2006) point out that materials with high embodied energy are highly likely to also have high embodied carbon. Much attention has been paid to the relative contributions of operational and embodied energy and carbon to the total life cycle impacts. Adalberth's (1997) life cycle energy analysis of three domestic properties in Sweden showed that operational energy use was 85% of the lifecycle and embodied energy just 15%. Cole and Kernan's

(1996) life cycle energy assessment of commercial offices built to contemporary Canadian building standards showed similar results, with embodied energy just 10-20% of the lifecycle.

The consensus of the majority of papers reviewed for this research was that the operational, or use phase of the buildings is responsible for the majority of energy consumption and carbon emissions. A number of authors draw conclusions in a similar vein to those of Scheuer et al., who assess a range of life cycle environmental impacts for a university building in the US and conclude that 'optimization of operations phase performance should still be the primary emphasis for design, until it is evident that there is a significant shift in distribution of life cycle burdens' (2003, p. 1061). Cole and Kernan predicted that due to energy efficiency improvements, embodied energy could increase to 45-55% of the life cycle in the early part of 21st century (1996, p. 314). This view is supported by recent studies by Darby which led him to conclude that for many new buildings, the embodied is likely to be responsible for around 40% of life cycle carbon emissions (2014, p. 284).

A significant majority of published studies of the life cycle or embodied carbon of buildings assess either residential properties or commercial offices. This is clear from looking at some relatively recent literature reviews. Ramesh et al. (2010) found that of 25 published works, 17 were categorised as residential and the remaining 8 were offices. Cabeza et al. (2014) found 26 studies of residential properties (including high rise, multi-residential buildings), and 8 studies of commercial offices. There are a small number of exceptions such as educational buildings (Cabeza et al. find 4 such studies) or other types of commercial buildings (e.g. Buchanan & Honey, 1994). Only one embodied carbon assessment of a supermarket building was found in a publication produced as part of a UK steel industry initiative (Target Zero, 2011). Densley Tingley (2013) has also presented results for a supermarket, but these are based on the same data as the Target Zero report.

2.3.2 Sainsbury's Prior Work on Embodied Carbon

Sainsbury's have commissioned five life cycle carbon assessments of supermarket buildings constructed between 2007 and 2011. These detail the assessment of six supermarket designs and one petrol station and were all undertaken by the same team of consultants. The reports provide some useful insights into commercial approaches to embodied carbon assessment of retail buildings. However, the most recent is now more than six years old and methods and data have continued to develop. For example, the studies use data from the Inventory of Carbon and Energy v1.6, which was superseded by version 2.0 in January 2011 (Hammond & Jones, 2011). Version 1.6 only provided data for CO_2 emissions, not CO_2e and so the consultants employed by Sainsbury's derived their own factors for increasing emissions to reflect other GHGs (dCarbon8, 2008).

The reports do not provide full details of the carbon factors used for each material. Thus there is a lack of transparency in the results which prevents replication and restricts the level of interrogation and analysis that is possible. The table in Appendix A: provides an overview of the attributes of each of the studies including the data sources used and assumptions made. Whilst the approach is consistent for all the assessments, there is some variation in the data sources used to derive the material quantities and in a number of cases data has been drawn from secondary literature sources or from unpublished data held by the consultants. In a number of the reports, not enough detail is provided to determine which items have been calculated with primary and secondary data. Where this detail does exist, the reason for the use of secondary data appears to have been driven by a lack of primary data in certain areas such as fit out material quantities or site construction energy consumption.

The other notable variation between the studies is in the service life length that has been assumed for the operational phase of each store in the assessment. In the earlier studies the service life is assumed to be 30 years. Yet two stores were assessed on a 60 year service life and one report does not state the length of service life assumed. This detail has a notable impact on the results of operational carbon but also affects embodied carbon since this includes emissions from refurbishment of the building on a 10 yearly cycle.

The primary criticism of the approach from Sainsbury's perspective appears to be the labour intensiveness and hence the cost of each assessment. This was given as the main reason why Sainsbury's has not been able to extend this assessment approach to all its stores. According to Sainsbury's staff involved at the time, the collection and analysis of the material quantities was the most time consuming aspect of the work.

2.3.3 Variation and Lack of Comparability Between Results

Moncaster and Song (2012) have highlighted the significant variation in embodied energy and carbon values that can be found between different studies of buildings. Their review synthesises results from Ding (2004) and Sartori and Hestnes (2007) to give a range of embodied energy figures for residential buildings of 1.8 – 8.78 GJ/m^2. According to data presented by Dixit et al., (2010) the range amongst studies of commercial buildings is even greater at 4.3 – 19 GJ/m^2 as shown in Figure 2-2.

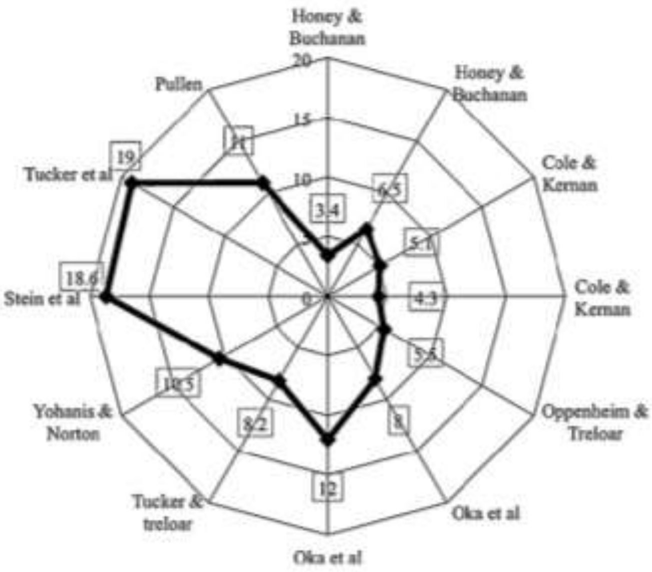

Figure 2-2: Embodied energy values for commercial buildings (Reproduced from Dixit et al., 2010, p. 1241)

This variation presents a challenge for businesses such as Sainsbury's that are looking for a method of consistently quantifying their embodied emissions and to benchmark their performance. The authors use a form of systematic literature review to identify ten different factors that affect this variation, which they give as:

1. System boundaries
2. Method of embodied energy analysis
3. Geographic location
4. Primary and delivered energy
5. Age of data
6. Data source
7. Completeness of data
8. Manufacturing technology
9. Feedstock energy consideration
10. Temporal representation

(Dixit et al., 2010, p. 1243)

These bear resemblance to Weidema and Wesnaes (1996) five parameters affecting data quality listed in 2.2.3 above. They recommend the development of standards to ensure consistency between studies in relation to these 10 parameters.

In Europe, the Centre for European Standardisation (CEN) has developed a framework for assessing the environmental impacts of buildings which consists of a standard for LCA carried out at the building level, EN 15978 (British Standards Institution, 2011a), and a standard for assessments of construction products, EN 15804 (British Standards Institution, 2014a). These standards are closely aligned to the ISO 14040 series of standards for LCA and also follow the process analysis approach. It was found that much of the recent literature on embodied carbon undertaken in Europe makes reference to these standards (Pomponi, D'Amico, & Moncaster, 2017; Hoxha et al., 2017; Pomponi & Moncaster, 2016; Schwartz et al., 2016; Lasvaux et al., 2015; Darby, 2014). There is also evidence to suggest that the standards have broad acceptance in industry (Moncaster & Pomponi, 2016; UK Green Building Council, 2014). These standards were published after the work of Dixit et al., and to date no work has sought to assess whether their application has, in fact, led to greater consistency and comparability of outcomes for embodied carbon assessments of buildings. The standards divide the building life cycle into stages known as modules. These are shown in Figure 2-3 below. It has been observed in the course of this research that this common format for reporting results according to the relevant life cycle stage, where it has been applied, does facilitate more ready comparison of outcomes.

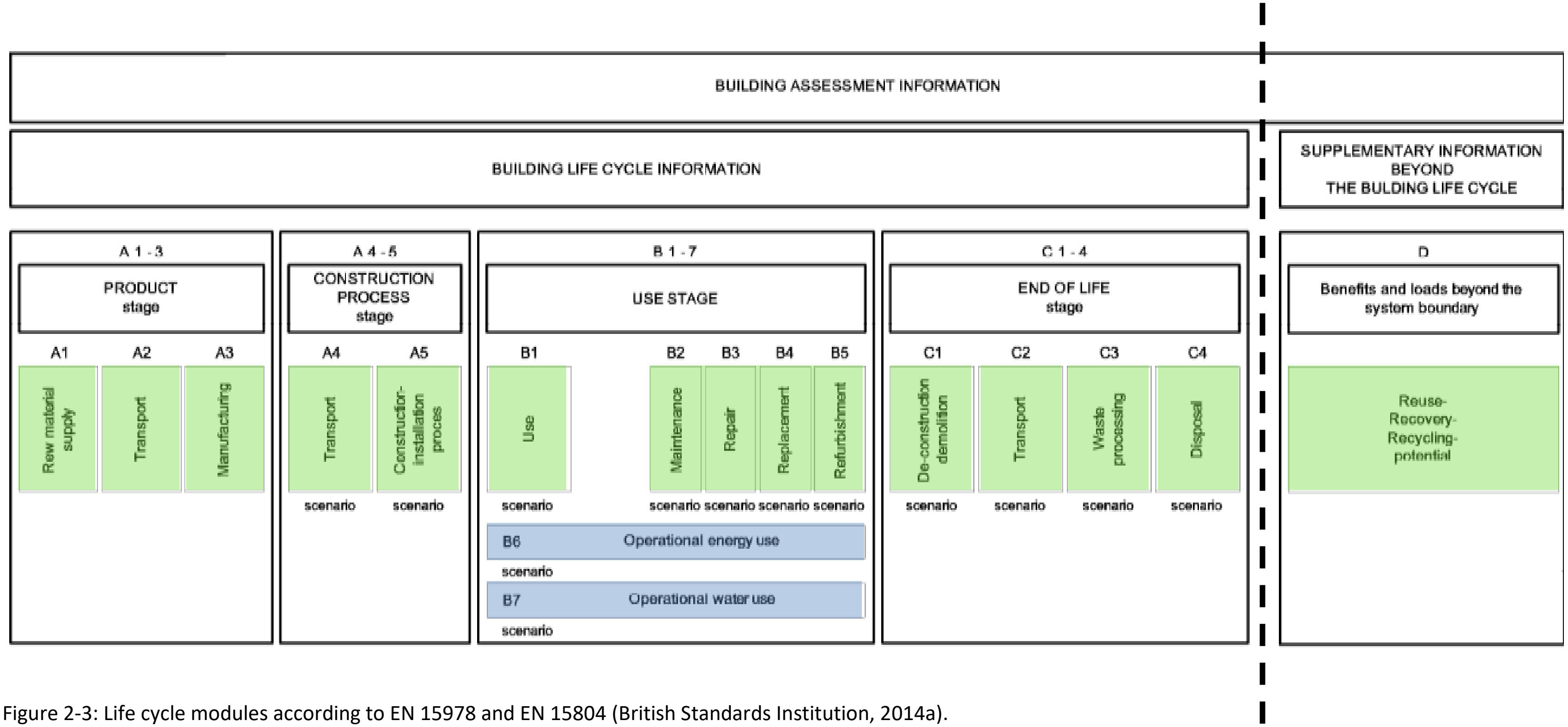

Figure 2-3: Life cycle modules according to EN 15978 and EN 15804 (British Standards Institution, 2014a).
Green = contributes to embodied carbon. Blue = contributes to operational Carbon

2.4 Data Sources: Carbon Factors

An embodied carbon assessment of a building requires two sets of data (RICS, 2012a). The first are the inputs to and outputs from the building. For process analysis, these take the form of physical quantities of materials and energy at each life cycle stage. For EEIO methods, these data are estimated based on economic transactions between sectors. The second set of data required is the corresponding carbon factors for each of these inputs and outputs. Carbon factors provide an estimate of the total global warming potential (GWP) of all greenhouse gas emissions associated with the production, use and disposal of a given unit of material or the consumption of a unit of fuel or electricity. The GWP of each greenhouse gas is characterized as the GWP of an equivalent amount of carbon dioxide.

For example, each kilogram of methane released into the atmosphere is estimated to have the equivalent GWP of 25 kilograms of carbon dioxide (IPCC, 2007). Hence carbon factors which account for multiple greenhouse gases are reported in units of carbon dioxide equivalent, CO_2e.

For materials, carbon factors are typically reported in either mass or volumetric terms with units of $kgCO_2e$ per kg (or tonne) or per cubic meter (or other appropriate volumetric unit) of material (e.g. Hammond & Jones, 2011). For energy, carbon factors are reported either per megajoule or KWh of electricity, or per physical unit of fuel consumed (e.g. litres) (e.g. Department for Environment, Food and Rural Affairs, 2015).

Building level embodied carbon assessments typically make use of secondary sources of carbon factor data since producing or obtaining primary data would be too resource intensive (G. J. Treloar et al., 2000). A variety of different sources of data exist and in reviewing the literature for this research, six main sources were identified which are commonly used. These are:

- Factors derived/aggregated from literature review
- Industry data – e.g. carbon factors provided by a product supplier or industry body but which are not published as part of a formal Environmental Product Declaration (EPD) (see 2.4.6 below)
- Government data – generic carbon factors provided by national governments, such as those released by Defra (2015) for use by UK organisations compiling annual carbon emission reports
- Factor from a commercial LCA database such as GaBi or Ecoinvent
- Factor from a PAS 2050 compliant carbon footprint

- PAS 2050 Carbon Footprint (see 2.4.5 below)
- Factor from an EPD (EN 15804 compliant)

2.4.1 Literature derived carbon factors

These sources provide generic carbon factors for a range of materials that have been derived by literature review. The examples reviewed for this research are geographically specific such as the work by Alcorn and colleagues in New Zealand (Baird, Alcorn, & Haslam, 1997; eg. Alcorn, 1996; Alcorn & Baird, 1996) or Hammond and Jones' *Inventory of Carbon and Energy* (ICE) which has been widely used in the UK (2008, 2011). In these works, data have been collated from a range of different secondary sources and aggregated or averaged to provide a single value of embodied carbon for each material. The methods used to determine a single value from the range of values in the literature vary between the different datasets. The secondary data that they draw on include peer-reviewed, academic work as well as data from industry and trade associations or specific companies. Examples of such sources include work by the British Cement Association (Clear et al. (1995) in Hammond & Jones, 2011) or the Association of Plastics Manufacturers in Europe (Boustead (2003) in Hammond & Jones, 2011). The ICE data, despite being most recently updated in 2011, continues to be a commonly used source of carbon factors amongst UK industry practitioners (Moncaster & Pomponi, 2016). It has a number of limitations including its age, which is exacerbated by the fact that it is based on data that are, in some cases, considerably older. It also only provides data for the first part of the material life cycle, i.e. for the product stage or modules A1-3 according to EN 15804 (see Figure 2-3).

2.4.2 Industry Data

Much of the most recently published data from industry bodies or individual companies is released in the form of EPD, which are discussed separately in 2.4.6 below. However there are examples of non-EPD data from industry for a range of materials. The World Steel Association produces an extensive set of life cycle inventory[1] (LCI) data for steel which is freely available for non-commercial use (World Steel Association, 2011). This in turn has been used by the Steel Construction Institute (SCI) and the British Construction Steelwork Association (BCSA) (2014) to produce embodied carbon data for different types of steel used in buildings. Embodied carbon data are available from the Mineral Product Association (2012) for cement and concrete in the UK. One of the UK industry bodies for timber has released a number of LCA results for different types of timber supplied in the UK (Wood

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[1] A life cycle inventory (LCI) is one of the four stages of a life cycle assessment (LCA) according to ISO 14040 and is the stage where the material and energy flows into and out of a product system are quantified (British Standards Institution, 2006a)(British Standards Institution, 2006a). In the subsequent life cycle impact assessment (LCIA), the environmental effects of these flows, in terms of global warming potential (in the case of carbon emissions) or other impact categories are assessed and characterised.

for Good, 2013a). As with the literature based carbon factors described above, these are examples of generic data, based on industry average production. The level of detail available regarding the scope and boundaries of the studies and the assumptions that have been made varies considerably. The data from the World Steel Association are provided with an 88 page methodology report, whilst the report accompanying the Mineral Product Association data is considerably less extensive, at eight pages. Further differences between the methodologies of some of the key sources of industry data, including the two mentioned here, are analysed and discussed in Chapters 6 and 7 of the thesis.

2.4.3 Government Data

Government data are typically based on national inventories or statistics meaning they are representative of typical carbon emissions for materials or activities in a given country. In the UK, Government departments and agencies have published a number of sources of carbon factors relevant for construction materials. The Department for Environment Food and Rural Affairs (Defra) (2015) publishes a set of carbon factors for use by organisations in annual GHG reporting. This includes carbon factors for some activities that are relevant to construction, including transport emissions for freight, emissions for grid electricity and fuels, and emissions from waste disposal. The Environment Agency (2014) produced an embodied carbon calculator in the form of a spreadsheet. The spreadsheet was free to download from the Environment Agency website at the time the research was undertaken. The data allow the user to assess embodied carbon for materials, transport, site energy use, and waste management as well as personnel travel. This is broadly equivalent to the modules A1-5 of EN 15978 and 15804, or cradle to site. Much of the cradle to gate (A1-3) emissions data is taken from the ICE database (Hammond & Jones, 2011) and is therefore literature derived data rather than Government data. Moreover, the calculator was developed for use on the Environment Agency's own projects, which are described as being predominantly 'fluvial and coastal construction works' (User guide section of Environment Agency, 2014) and the material carbon factors listed are predominantly focused on materials used in civil engineering.

In studies reviewed for this research, examples of the use of Government data in embodied carbon assessments of buildings included assessing emissions from electricity and fuel consumption at different stages of the life cycle (Darby, 2014; Azari-N & Kim, 2012). There are also examples of Government data sources for full LCA inventories of materials, such as the US Life Cycle Inventory Database (Reference 26 in Azari-N & Kim, 2012). Moreover, when EEIO or hybrid assessments are conducted, the input-output data are typically derived from Government sources (e.g. Kofoworola & Gheewala, 2009).

2.4.4 Commercial LCA

Commercial LCA packages comprise a software interface for conducting assessments and one or more databases of LCI and impact assessment (LCIA) data (thinkstep, n.d.). LCI data are the basic flows of materials and energy into and out of a product system, whilst LCIA data are used to determine the potential environmental impact of each of these flows. The two most widely used commercial LCA packages are SimaPro and GaBi. Both provide access to the Ecoinvent LCI database (Moncaster & Song, 2012) whilst GaBi also allows use of the proprietary GaBi LCI database (thinkstep) (e.g. Peuportier, 2001). Neither the Ecoinvent nor the Gabi databases are freely available but require subscription fees to be paid. Examples of studies of buildings that use data from these sources include Peuportier (2001), who conducted full LCA of single-family dwellings in France, and Darby (2014), who assesses embodied carbon of a number of different public and commercial buildings in the UK. Intini and Kühtz (2011) used commercial LCA to compare LCA results of virgin and recycled insulation material in buildings, whilst Darby (2014) also used it as a means of estimating embodied carbon factors for steel, concrete, timber and aluminium.

2.4.5 PAS 2050 Carbon Footprint

Publically available specification (PAS) 2050 is a UK standard for producing a life cycle carbon assessment of a product or service. PAS 2050 compliant studies may be used in type II environmental labelling, which are ‘self-declared environmental claims’ (British Standards Institution, 2011b, p. 1). Whilst this standard has been listed and discussed in reviews of embodied carbon data (e.g. Darby, 2014; Moncaster & Song, 2012), no published embodied carbon assessments of buildings were found which used data from a PAS 2050 compliant study or environmental label. In discussions that took place during the elicitations that were conducted as part of this research (see Chapters 5, 6 and 7), expert participants confirmed that they have made use of such data in commercial studies.

2.4.6 Environmental Product Declarations (EPDs)

EPDs underpin the new EU standards for conducting environmental sustainability assessments of buildings that were introduced in section 2.3.3 above. An EPD contains the results of an LCA for a particular material or product and as such, most have been produced using commercial LCA software such as SimaPro or GaBi. The main difference between commercial LCA data (as defined here) and EPD data is that the former is generic data taken directly from the software and based on the software provider’s proprietary LCI databases, whereas EPD are based on primary data from a manufacturer or group of manufacturers. This primary data may have been combined with some secondary commercial LCA data in order to conduct a full life cycle assessment. There are examples of industry or average EPDs (e.g. Institut Bauen und Umwelt e.V., 2013) and manufacturer or product specific

EPDs (e.g. Institut Bauen und Umwelt e.V., 2016). An EPD is a type III declaration, which means it must be independently reviewed and verified prior to publication. EPDs may have one of three possible scopes according to EN 15804. These are cradle to gate (only modules A1-3), cradle to gate with options, (modules A1-3 plus one or more other modules), or cradle to grave (all modules assessed and reported) (British Standards Institution, 2014a). According to a recent review by Anderson (2017), the number of EPDs published globally has increased significantly in recent years with some 3500 available in early 2017. She also found that, cradle to gate EPDs account for 17%, cradle to grave EPDs represent 25% of the total and the remainder are cradle to grave with options. A number of authors have expressed the view that the growth in availability of EPD will improve the data availability for conducting embodied carbon assessments and may also improve the comparability of studies (Darby, 2014; Moncaster & Symons, 2013; Moncaster & Song, 2012).

2.5 Material Quantities

In addition to carbon factor data, an embodied carbon assessment requires data on the quantities of material used to construct a building, and the fuels or electricity used in the construction and demolition. When an assessment is conducted during the design stage of a building, materials quantities are estimated from the design drawings (Häkkinen et al., 2015; Rai et al., 2011; Hammond & Jones, 2008) and documents whilst energy used in construction and demolition must be estimated, perhaps using data from previous construction projects.

Under the approach set out in EN 15978 and EN 15804, fuel and electricity consumption at each stage of the life cycle are included in the carbon factors of the individual materials and products used in the construction of the building. Thus to be EN 15804 compliant, a cradle-to-grave EPD for a material must include data on the carbon emissions (and other LCA impact categories) for the construction and demolition activities (British Standards Institution, 2014a). Therefore, by adopting this approach, and provided the relevant compliant cradle-to-grave EPDs are available, it is only necessary to obtain material quantities for the building. Fuel and electricity consumption is then accounted for in the carbon factors for the relevant life cycle stage (see life cycle modules in Figure 2-3) for each material.

This differs from approaches to calculating embodied carbon (or energy) that have been used in some studies pre-dating the development of these standards. Equation 2.1 is adapted from Richardson et al. (2014, p. 2) and shows how some previous studies have approached calculating embodied carbon and/or energy for a building (Ramesh, Prakash, & Shukla, 2010).

$$EC = \langle \sum m_i CF_{mi} + E_c CF_{EC} \rangle + \langle \sum m_i CF_i [(L_b / L_{mi}) - 1] \rangle + \langle E_D CF_{ED} \rangle \qquad \text{Equation 2.1}$$

Embodied carbon, adapted from Richardson et al. (2014, p. 2)

Where:

- *EC* is the embodied carbon of the building from cradle-to-grave
- The terms demarcated within chevrons (from left to right) represent embodied carbon of initial construction, embodied carbon of subsequent refurbishment, and embodied carbon of demolition respectively. In these terms,
- m_i is the quantity of material *i*,
- CF_{mi} is the carbon factor of material *i* per unit;
- E_c is the construction energy requirement,
- CF_{EC} is the carbon factor of the construction energy
- L_b is the assumed service life of the building in years;
- L_{mi} is the assumed service life of components in years;
- E_D is the energy requirements for demolition;
- CF_{ED} is the carbon factor of the demolition energy

By contrast, Equation 2.2 illustrates the approach adopted in the European standards (note that this equation is not in the standards)

$$EC = \sum m_i (CF_{A1-3} + CF_{A4-5} + CF_{B1-5} + CF_{C1-4})$$

Equation 2.2

Embodied Carbon based on the approach of EN 15987 (British Standards Institution, 2011a)

Where:

- EC is the embodied carbon of the building from cradle-to-grave
- m_i is the quantity of material *i*,
- $CF_{A1\text{-}3}$ *is the carbon factor for the product life cycle stage*
- $CF_{A4\text{-}5}$ *is the carbon factor for the construction life cycle stage*
- $CF_{B1\text{-}5}$ *is the carbon factor for the use stage*
- $CF_{C1\text{-}4}$ *is the carbon factor for the demolition and disposal stage*

The availability of cradle-to-grave EPD data is therefore an important factor affecting how viable the approach of the European standards will be in practice (see section 4.6 for a further discussion of this issue).

2.5.1 Quantity Take-off Methods Using Building Information Modelling (BIM)

The process of extracting material quantities from design documentation is known as a quantity take-off (QTO). Traditionally this has been conducted for the purposes of cost estimation and was a manual process of visualisation and taking scaled measurements from two dimensional technical drawings (Shen & Issa, 2010). Three dimensional computer aided design (CAD) can improve the QTO process by aiding visualisation and comprehension of the spatial relationships of different elements of the building (Shen & Issa, 2010). The development of BIM, is seen as a further opportunity to improve the efficiency of QTO processes (Cheung et al., 2012; Sattineni & Bradford, 2011). The UK BIM Task Group defines BIM as 'the creation, collation and exchange of shared 3D models and intelligent, structured data attached to them.' (2013). This intelligent data, sometimes referred to as meta-data (Schwartz et al., 2016), may specify additional information about a material, its composition, supplier, and so forth. It has also been proposed that BIM can be integrated with LCA to facilitate improved assessment of environmental impacts

2.6 'Green-BIM'

Potential advantages of adopting BIM processes have been discussed and reviewed by academics, practitioners and policy makers. Commonly cited benefits include capital and operational cost savings, efficiency improvements, and increased profitability in the design and delivery of buildings (McGraw Hill Construction, 2014; Bryde, Broquetas, & Volm, 2013; Barlish & Sullivan, 2012; British Standards Institution, 2012). Applications of BIM that seek to achieve improvements in environmental performance of buildings have sometimes been referred to as 'Green-BIM' (Wong & Zhou, 2015; Krygiel & Nies, 2008). Different proposals have been put forward for ways of implementing green-BIM. The *BIM Investors Report* published in collaboration with the UK Department for Business Innovation and Skills claims that with respect to the 'green agenda […] an integrated approach using BIM data will ensure that assets can be delivered and maintained in the cleanest, leanest way possible' (British Standards Institution, 2012, p. 1). This claim is difficult to justify without further qualification of what data is used and for what purpose.

One approach which more directly addresses these questions is the integration of BIM enabled software with sustainability rating schemes such as BREEAM or LEED[2]. BIM software is used as a tool

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[2] BREEAM (Building Research Establishment Environmental Assessment Method) is run by the UK BRE and is described on their website as 'the world's leading sustainability assessment method for masterplanning projects, infrastructure and buildings.' (BRE, 2015)

to support the generation of evidence necessary to demonstrate compliance with a chosen certification scheme (Jalaei & Jrade, 2015; Azhar et al., 2011)

Other researchers have explored and demonstrated ways to integrate BIM and energy modelling of buildings. BREEAM and LEED have a category of credits relating to energy consumption, so typically the use of BIM to demonstrate compliance takes account of this aspect. But studies have also looked specifically at the ability of BIM to facilitate operational energy and carbon analysis in their own right (e.g. Kim et al., 2016; Ham & Golparvar-Fard, 2015).

Methods for achieving these green-BIM objectives were found to adopt one of two techniques. The first is to incorporate a new process within BIM enabled software by using the native expansion capabilities available in some of these programmes. Autodesk Revit (Autodesk, 2014), for example, offers the possibility to incorporate plug-ins; small applications written by the user to automate a process or to expand the features of the software. This technique was used by Jalaei and Jrade (2015) to facilitate automatic checks for compliance with certain LEED credits and to calculate LEED registration fees. The alternative is to use the data exchange features of BIM enabled software to export the model, or parts of the model, for analysis in a second software package. This was the approach used by Ham and Golparvar-Fard (2015) in their proposed method for supplementing BIM models with empirically determined thermal properties. Other academic papers have also taken this approach (Liu, Meng, & Tam, 2015). Commercial examples of this also exist, including the simulation package DesignBuilder, which can accept BIM models exported in gbXML (green building extensible mark-up language) format (US Department of Energy), and IES VE, a package for thermal modelling and various other energy related performance analysis tools, which can accept models exported from AutoDesk's Revit (IES, 2015), provided these are exported using a dedicated plug-in that helps ensure compatibility.

One advantage of the data export technique is that it does not require knowledge of programming which would be needed to create plug-ins. However, in some cases the data exchange only works in one direction. Maile et al. (2007) reviewed several energy simulation packages, taking into account the interoperability and data exchange. As well as highlighting errors in the initial transfer of data from the BIM to the energy modelling tool, their report shows that most tools have no, or severely limited, reverse data exchange. This means that any adaptations made in the energy model to improve the simulated energy performance cannot be easily transferred back to the original BIM model in the

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LEED (Leadership in Energy and Environmental Design) is the US Green Building Council's assessment scheme and is described on their website as 'the most widely used third-party verification for green buildings.' (U.S. Green Building Council, 2016).

design software. Thus under this approach to green-BIM, changes to the design which are required to achieve the environmental performance improvement may need to be made manually in the design software.

2.6.1 BIM and LCA Integration

These two approaches have also both been proposed to integrate BIM with environmental impact data (Díaz & Antön, 2014). Examples of how each could be implemented for the purposes of conducting either a full LCA or an embodied carbon assessment have been developed. Schwartz et al. (2016) propose a method for integrating LCA data into the BIM model within the BIM design software (Revit) without the need to export the data. Jrade and Abdulla (2012) used the industry foundation class (IFC) file format (a common BIM file format supported by many design software packages) as a means of extracting data from BIM and then importing it into an existing commercial LCA calculation tool.

Díaz and Antön reviewed approaches to integrating BIM with LCA and suggest that the following four factors are important for effective implementation:

1. Avoidance of data re-entry
2. Ease of use
3. Real-time appraisal
4. Whole building assessment

(Díaz & Antön, 2014, p. 287)

These criteria are equally applicable for integrating BIM and embodied carbon assessments. The first three criteria have an effect on the efficiency with which an assessment can be conducted. The avoidance of data re-entry and the ease of use both directly affect the amount of time required to conduct an assessment. Real-time appraisal means that the effects of different design changes on the embodied carbon of the building can be evaluated as the design is being developed. This also ensures an efficient workflow, since the causal link between design changes and negative or positive effects on the embodied carbon results can be more readily appreciated. Thus embodied carbon impacts can be addressed before the design progresses and changes become more difficult.

The fourth criterion relates to the comprehensiveness of the assessment which can be undertaken, and the authors suggest that assessment of the whole building should be complemented with the possibility of evaluating the environmental impacts of sub-sections of the construction. They do not go on to assess whether the information and data in a typical BIM model is suitable for conducting a whole building assessment. This is an area which has not been explored in depth. Studies reviewed for this research that assessed the environmental impacts of a building using a BIM integrated approach were based on models created specifically for the purpose (Schwartz et al., 2016; Stadel et al., 2011). Basbagill et al. (2013) used a real office building as a case study for their work on integrating LCA and BIM. However, their approach was to evaluate a large number of possible materials for each element of the building. They therefore used only the basic geometry from the BIM model and not any of the additional meta-data.

The potential to utilise BIM as a source of data for conducting embodied carbon assessments is the subject of ongoing research and the literature reviewed here indicates that there are still challenges to be overcome in implementing this. Creating a link between the BIM data and the carbon factor data in order to prevent or minimise the amount of data re-entry and evaluating how suitable typical BIM models currently are for this application are both key areas that require further investigation.

The use of a BIM integrated approach to conducting embodied carbon assessments may improve their efficiency. Moreover, if assessments can be conducted in near real-time during the design, then BIM can facilitate more effective decision making to reduce embodied carbon. However, the use of BIM in this way does not address some of the limitations of current methods and data discussed in section 2.2 above which lead to a lack of comparability of results. These limitations cause uncertainty about the embodied carbon results for the building. They also lead to uncertainty about the reliability of comparative assessments of the embodied carbon effects of different design options.

2.7 Uncertainty

Uncertainty is commonly understood to refer to a state of doubt or lack of clarity (Merriam-Webster). In academic literature and research, the term may be interpreted differently in different fields. Heijungs and Huijbregts state that ‘a fully satisfying definition may be difficult to agree upon’ (2004, p. 2). However, they go on to suggest that in the context of LCA and other types of modelling uncertainty is related to ‘the problem of using information that is unavailable, wrong, unreliable, or that show a certain degree of variability’, (2004, p. 2), The authors also explain that this problem can occur in the data, the model relationships or equations, and the methodological choices and assumptions upon which the model is based.

2.7.1 Uncertainty Typologies

A number of formalised categories have been proposed to distinguish between uncertainties with different characteristics. One such typology which is commonly referenced was first detailed in guidance published by the United States Environmental Protection Agency (US EPA) and defines three categories of uncertainties. These are parameter, model and scenario uncertainties (Basket et al., 1995) and they relate to the three problem areas identified by Heijungs and Huijbregts. Parameter uncertainty relates to uncertain data inputs to the model; model uncertainty relates to the relationships or equations that make up the model; and scenario uncertainty is the term applied to methodological choices or assumptions. Other authors have suggested additional categories such as epistemic and aleatory uncertainty (Bedford & Cooke, 2001), which distinguish between those uncertainties that can be reduced through improved knowledge and those which are due to natural variabilities of the system to be modelled. Walker *et al.* (2003) have drawn together a number of the key characteristics which distinguish different uncertainties into a conceptual framework. In this framework, uncertainty is defined and categorised in three ways, which the authors refer to as three dimensions of uncertainty. These dimensions are the location, level and nature (see Figure 2-4). *Location* is analogous to the US EPA typology in that it specifies whether uncertainty is in the input data (input uncertainty), in the model's relationships or equations (model uncertainty), or in the assumptions and choices on which the model is based (context uncertainty). The *level* of uncertainty is a scale which is intended to codify how certain or uncertain something is. The *level* of uncertainty therefore ranges from determinism or absolute certainty at one end of the scale, to absolute uncertainty or unknown ignorance at the other. Between these extremes Walker et al. differentiate between statistical uncertainty, where probabilities can be estimated; scenario uncertainty, where different outcomes are anticipated but the likelihood or probability of each is not known; and recognised ignorance, or "known unknowns" where 'the scientific basis for developing scenarios is weak' (Walker et al., 2003, p. 12). Finally, the *nature* dimension encompasses aleatory (here termed variability) and epistemic uncertainty.

The three dimensions framework has been widely cited and applied in studies of uncertainty and has over 500 CrossRef citations and more than 1200 citations listed in Google Scholar. One of its advantages over other typologies which have been proposed is that it recognises that uncertainties have multiple characteristics. For example uncertainty in a data input may be epistemic or variable in nature and may be relatively more or less uncertain than other data. Walker et al.'s typology recognises this multi-dimensionality and allows sources of uncertainty to be categorized in matrix form according to each of the dimensions.

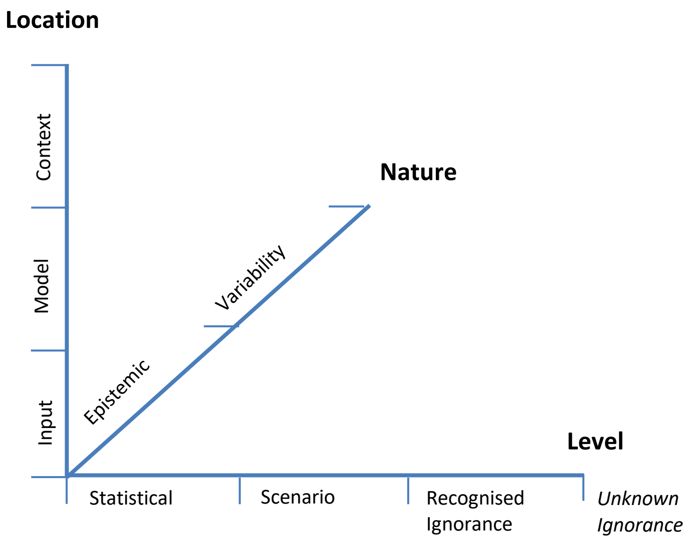


Figure 2-4: Three dimensions of uncertainty (adapted from Walker et al., 2003)

2.7.2 Treatment of Uncertainty

Heijungs & Huijbregts discuss different approaches to dealing with uncertainty in LCA. They identify four main categories of approach as being scientific, constructivist, legal and statistical (2004, p. 3). The scientific approach is to conduct further research in order to improve or update uncertain data or relationships in the model. The constructivist approach seeks to build or identify expert consensus around a particular set of data, model relationships or set of assumptions or methods. The legal approach is to rely on standards to determine common methods. The authors point out that the 'first three of these approaches aim to reduce uncertainty, while the last approach aims to explicitly incorporate it' (2004, p. 3). This fourth approach is to use statistical techniques to quantify confidence or uncertainty ranges. These categories are useful in that they make direct comparison of these different approaches, acknowledging that each is essentially dealing with the same problem, namely that of uncertainty. The categories are perhaps less distinct than the authors imply. For example the process of developing standards is often based on the work of committees of experts who may consult with key stakeholders (for example see Ilomäki, 2016) to ensure that standards have broad consensus. Thus the legal approach is largely contingent on the constructivist approach.

Importantly, Heijungs and Huijbregts recognise that different actors may prefer one approach over another (2004, p. 3). Thus in academic research, the scientific approach is often pursued and researchers may conduct detailed LCA of particular construction materials to improve the available data (e.g. Darby, 2014; Purnell & Black, 2012; Koroneos, Roumbas, & Moussiopoulos, 2005). For industry practitioners, Heijungs and Huijbregts expect the legal approach, of relying on data produced in adherence to independent standards such as BS EN 15804, to be most common. There is evidence to support this view, for example the establishment of ECO-Platform (2014). Eco-Platform is an online database of certified EPDs established by a consortium of EU organisations including construction sector trade associations and LCA practitioners. In the examples given here, where these approaches have been applied, the problem of uncertainty is typically implicit rather than explicitly identified. They therefore do not explore or identify the types of uncertainty that affect building LCA and embodied carbon assessments and so may not appropriately deal with some types of uncertainty. For example, the scientific approach cannot address variability uncertainty. The legal or constructivist approach on the other hand may provide consistent outcomes, but may lead to important alternative methodological choices being overlooked.

In examples of studies where uncertainty has been explicitly identified, it is often the statistical approach which is adopted (eg. Stephan, Crawford, & De Myttenaere, 2012) to determine probability distributions for key model inputs and thus evaluate the results in terms of probable outcomes. As Heijungs and Huijbregts point out, this has the advantage of explicitly acknowledging and incorporating uncertainty into the modelled outcomes. The approach also has drawbacks, however. It is usually necessary to collate large datasets from which distributions can be derived (Pomponi, D'Amico, & Moncaster, 2017). This may be the reason that such methods are viewed with scepticism by some industry practitioners (Moncaster & Pomponi, 2016) who may therefore prefer to rely on the other approaches. Moreover, as the name implies, the quantitative methods of the statistical approach are best suited to assessing uncertainties at the statistical level. Uncertainties at the scenario or recognised ignorance level are not readily represented by distributions and so this approach alone may not adequately capture all relevant uncertainties.

In choosing an approach to dealing with uncertainty it is therefore important to recognise that 'uncertainty should be seen as a red thread throughout the modelling study starting from the very beginning' (Refsgaard et al., 2007, p. 1555). This means that the uncertainty assessment approach and method selected should take account of the types of uncertainty that are relevant to the study (Van Der Sluijs et al., 2004), the intended use of the uncertainty results, and the perspective of the actors and stakeholders involved.

2.7.3 Uncertainty Assessment Methods

For a value which is estimated to be a function of a number of input parameters, such as $y = f(x_1, x_2, x_3, \dots, x_n)$, uncertainty may be located in the input parameters, x_1 *to* x_n, in the function, and in the assumptions made in selecting the function and inputs to estimate *y*.

If each of the values of the input parameters x_1 to x_n is subject to uncertainty, then these may be replaced with uncertainty ranges. Quantitative uncertainty assessment methods are those which allow the resultant uncertainty range in the outcome, *y*, to be evaluated for a set of known uncertainty ranges for some or all of the input parameters. In order to evaluate the effects on *y* of uncertainties relating to the function or the assumptions underpinning the function, a combination of quantitative and qualitative methods must be applied.

The Dutch National Institute for Public Health and the Environment (RIVM) has produced a tool catalogue for uncertainty assessment (Van der Sluijs et al., 2004). The guide describes different uncertainty assessment methods in detail and also provides an indication of which types of uncertainty the different methods are most suited to dealing with. A summary of their recommendations is shown in Table 2-1 and a similar table can be found in Refsgaard et al. (2007 Table 5)

Table 2-1: Uncertainty assessment methods grouped by their suitability for assessing different types of uncertainty according to the RIVM *Tool Catalogue for Uncertainty Assessment* (2004, p. 6)

	Location		
Level	**Model Context**	**Model Structure**	**Model Inputs**
Statistical	Sensitivity Analysis Expert Elicitation	Sensitivity Analysis Expert Elicitation Model Quality Checklist	Sensitivity Analysis Error Propagation Monte-Carlo Analysis Expert Elicitation
Scenario	Scenario Analysis Expert Elicitation	Scenario Analysis	Scenario Analysis Expert Elicitation
Recognized Ignorance	Scenario Analysis Model Quality Checklist NUSAP Expert Elicitation	NUSAP Model Quality Checklist	Scenario Analysis NUSAP Model Quality Checklist Expert Elicitation
NUSAP = Numeral, Unit, Spread, Assessment, Pedigree – see Ravetz (n.d.) or Van der Sluijs (2005) for details			

The methods can be divided into those that are primarily quantitative in nature and those which have both quantitative and qualitative aspects to their approach. The exclusively quantitative methods identified are sensitivity analysis, error propagation and Monte-Carlo analysis.

Sensitivity analysis methods are divided between local and global (Saltelli & Annoni, 2010). Local sensitivity analysis explores the sensitivity of the results to selected parameters by altering the value of each parameter independently. It is sometimes also called *one-at-a-time* (OAT) sensitivity analysis because of the way parameters are altered. By contrast, global sensitivity analysis considers the interdependencies of multiple model parameters and can be conducted using methods such as the Morris method (Cariboni et al., 2007) or Monte-Carlo simulation(Van der Sluijs et al., 2004, p. 8). Error propagation refers to the use of a set of standard rules for evaluating the effects of uncertainty in input parameters to a mathematical equation and is limited to applications where uncertainties are small and parameters are normally distributed (Van der Sluijs et al., 2004, p. 12). In Monte-Carlo simulation deterministic inputs are replaced with probability distributions. The calculation of the desired value is performed several thousand times and for each iteration a different set of input values is chosen based on the probability distributions defined (e.g. Lo, Ma, & Lo, 2005). These distributions can be derived from statistical data series or, if such data are not available, through expert judgement (Knol et al., 2010).

The remaining four methods all typically involve some element of qualitative assessment. In a scenario analysis, the different scenarios modelled are defined qualitatively rather than according to probabilities or statistical ranges (Walker et al., 2003). The model quality checklist is self-assessment process for those constructing models based on a series of questions. It is 'intended to help guard against poor practice and to focus modelling on the utility of results for a particular problem' and was designed for assessment of 'complex models spanning human and natural systems' (Van der Sluijs et al., 2004, p. 51). Similarly, expert elicitation is typically used where system complexity or a lack of data means that quantitative uncertainty ranges cannot be determined statistically. Expert judgments may be elicited on both quantitative and qualitative aspects of uncertainty.

There is overlap between the methods identified in the RIVM tool catalogue. For example, scenario analysis may be used to conduct a form of sensitivity analysis (e.g. Babaizadeh & Hassan, 2013; Peuportier, 2001). The NUSAP method combines expert elicitations with a quantitative technique such as Monte-Carlo analysis (e.g. Van der Sluijs et al., 2005).

NUSAP, was first developed by Funtowicz and Ravetz (1990, 1993) and its name is an acronym of five indicators or qualifiers of uncertainty. The first three are quantitative indicators; numeral, unit and spread. Together they communicate 'the inexactness of the information' (Funtowicz & Ravetz, 1990, p. 28), which may be assessed using a number of statistical methods . The last two indicators are more qualitative in nature. Assessment conveys a qualitative judgement about the information, for example whether a result is based on optimistic or pessimistic estimates. Finally, Pedigree is a semi-quantitative judgement of the quality of the data, focussing on the 'production process of the information' (Van Der Sluijs, Craye, Funtowicz, Kloprogge, Jerry Ravetz, et al., 2005). The pedigree of the data is determined by expert judgement using a pedigree or data quality matrix. The NUSAP approach of combining quantitative and qualitative methods has been successfully applied in a number of studies which sought to evaluate the effects of different levels of uncertainty located in the model inputs, structure and context. (Refsgaard et al., 2005, 2007; Van der Sluijs, Risbey, & Ravetz, 2005; Krayer von Krauss, Casman, & Small, 2004; Van Gijlswijk et al., 2003; Van der Sluijs et al., 2002). These studies do not necessarily adhere to the formal NUSAP notation as presented by Ravetz (n.d.), which addresses each of the five indicators of the acronym. Nevertheless, they show how the principle of combining qualitative and quantitative methods allows for a more comprehensive assessment of different types of uncertainty than is possible when only quantitative methods are used.

In research on qualitative assessment methods and studies that applied these methods, much attention has been paid to the effect of heuristic bias on subjective judgements, and how to mitigate this. Heuristics are 'reflexive mental operations used to make complex problems manageable' (Gilovich, Griffin, & Kahneman, 2002, p. i), or more simply stated, they can be thought of as 'rules of thumb' (Kynn, 2008, p. 242; Van Der Sluijs et al., 2004, p. 34). The work of Tversky and Kahneman (1975) has been highly influential in shaping both the theory of how heuristics influence expert judgements and also the methods used to avoid biases that these heuristics are said to introduce. They argue that three main heuristic processes form the basis of expert judgements and that each of these are subject to potential biases. The heuristic processes identified are representativeness, availability, and adjustment and anchoring. Representativeness refers to a tendency to assume that if A appears representative of B, then the probability that A is an example of B is judged to be high. Kynn (2008) illustrates this with an example: 'if Steve seems highly representative of an engineer, then the probability that he is an engineer is judged to be high even if the base rate of engineers in the population is low.' (p. 244). The availability heuristic is characterised by a person's tendency to judge things to be more likely based on how readily they can think of an example. Adjustment and anchoring are similar to availability and may occur when considering quantitative outcomes. In estimating a value for a parameter, a person may start with a known value for a related parameter and consider how much the parameter they wish to estimate might differ from this. This is known as adjustment. Anchoring describes the tendency of test subjects, observed by Tversky and Kahneman (1975), to fail to adjust enough away from an initial value, thus they are anchored, mentally, to that value. These heuristics are particularly widely discussed in literature and guidance documents on the subject of implementing expert elicitations (e.g. Knol et al., 2010; Slottje, van der Sluijs, & Knol, 2008; Risbey, Sluijs, & Ravetz, 2006; Van Der Sluijs, Craye, Funtowicz, Kloprogge, Jerome Ravetz, et al., 2005). Broadly, the recommended approach to mitigating biases is to make experts aware of the three heuristic processes and the biases they can introduce (Knol et al., 2010; Van Der Sluijs et al., 2004). In this way, the expert is able to consider whether their responses to a particular elicitation task may be biased by the heuristic process and may then revise their response accordingly.

However, Kynn (2008) has criticised the continued focus on the heuristics and biases theory in expert elicitation, pointing out that ‘more recent work has largely refuted many of the claims’ (p. 239) of Tversky and Kahneman’s original studies. She points to work in the field of psychology which suggests that ‘in applied contexts we should be equally concerned with not only *what* we ask experts to assess, but *how* we ask it.’ (Kynn, 2008, p. 240 [original emphases]).

2.7.4 Treatment of Uncertainty in Building Environmental Assessments

Ross et al. (2002) suggest that uncertainty has been widely discussed within the field of LCA since the late 1990s, linked to its inclusion in the ISO 14040 series standards. Within ISO 14040 there is a recommendation to consider uncertainty effects; a recommendation which becomes mandatory if the results are to be published for the purpose of comparative assertions (British Standards Institution, 2006b, 2006a). Despite this, in their review of 30 LCA reports published between 1997 and 2002, Ross et al. (2002) found that only 14 of these discussed uncertainty in the results. Of these, only three conducted an uncertainty assessment, either qualitative or quantitative.

In contrast to the ISO 14040 LCA standards, the more recently developed EU standards for assessing the environmental sustainability of buildings (EN 15978) and construction products (EN 15804) make no reference to uncertainty at all (British Standards Institution, 2014a, 2011a, 2010). It is perhaps therefore unsurprising that in published LCA and embodied carbon studies of buildings, little attention has been paid to the effects of uncertainty on results (Pomponi, D’Amico, & Moncaster, 2017; Pomponi & Moncaster, 2016; Cousins-Jenvey et al., 2014).

In order to ascertain the extent to which uncertainty has been addressed in the field of building LCA and embodied carbon assessments and the methods that have been applied, a review following the approach of Ross et al. (2002), was conducted. The starting point for this analysis was to collate a list of all papers cited in three relevant literature reviews (Cabeza et al., 2014; Ramesh, Prakash, & Shukla, 2010; Sartori & Hestnes, 2007),. Omitting duplicates and those studies for which full manuscripts were not available online, and selecting only papers published post-1997, when ‘uncertainties had been discussed widely in the literature’ (Ross, Evans, & Webber, 2002, p. 49), left 28 papers. This list was then updated by searching within Web of Science and Google Scholar for the key words *building* and *construction* in combination with either *LCA, embodied carbon* or *embodied energy.* A further 33 papers were identified in this way. Papers with no quantitative results of one or more environmental impacts for either a whole building or a construction product or material were excluded.

After initial selection, papers were divided into four types of study depending on whether they were an assessment of a whole building or single component or building element and those that were full LCA and those which were life cycle or embodied carbon assessments. Each paper was then searched for a number of terms that might indicate consideration of uncertainty. The terms were *uncertain* (including singular and plural references and *uncertainty*), *sensitivity*[3] (and *sensitive*)*, data quality, error,* and *variability* (*and variation*, *variance etc*.) These search terms were chosen based on a preliminary review of papers that were known to address uncertainty either explicitly or implicitly. In this preliminary sample, these were the terms most frequently used in the discussion of issues relevant to uncertainty. A summary of the results of this this review process is shown in Table 2-2 and the full details are reproduced in Appendix B:.

Table 2-2: Summary of the number of each type of study included in the systematic literature review

Total Papers		**60**
	Type of Study:	
	Building LCA	19
	Building embodied or life cycle carbon assessment	20
	Element or material LCA	20
	Element or material embodied or life cycle carbon assessment	1

---

[3] Saltelli and Annoni (2010)(2010) define uncertainty analysis (or assessment) and sensitivity analysis in terms of the questions they seek to answer. They suggest that the former seeks to answer 'How uncertain is this inference?' whilst the latter aims to determine 'Where is this uncertainty coming from?' (p. 1508). However, they acknowledge that the two terms are sometimes used interchangeably to encompass either or both objectives.

Table 2-3: Results of the systematic literature review showing which of 63 peer reviewed LCA or embodied/life cycle carbon assessment of buildings or building elements/materials included reference to uncertainty

Type of study	***Total positive search results*[1]**	**Search Terms[2]**					***No relevant use of search term*[3]**
		*Uncertain**	*Sensitiv**	*Data Quality*	*Error*	*Varia**	
Building LCA	**10**	9	10	4	5	5	**9**
Building embodied / life cycle carbon assessment	**16**	4	5	4	8	9	**4**
Material/ Component LCA	**8**	5	5	4	3	6	**12**
Material/ Component embodied / life cycle carbon assessment	**0**	0	0	0	0	0	**1**
Totals	**34**	18	20	12	16	20	**26**

1. Indicates number of studies of each type which contained relevant use of one or more of the search terms.
2. An asterisk denotes that alternative variations of the search terms such as singular/plural and adjectives/nouns were included in the search
3. A relevant use was one which related to uncertainty in the inputs or results of the study. Only the error and varia* search terms yielded non-relevant instances in four of the 33 papers listed here as having no relevant use.

The 34 papers which yielded relevant, positive results for the selected search terms were then reviewed in further detail. In total, 14 were found to contain a quantitative or qualitative assessment of uncertainty. This represents less than one quarter of the initial sample of studies.

Norris and Yost (2001) developed a prototype LCA tool called *Life Cycle Explorer* with the aim of improving the transparency of LCA results and data and the level of interactivity possible within the software tool. The tool included a function to undertake Monte-Carlo analysis for the purpose of assessing 'parameter and modelling uncertainties'. They discuss the importance of uncertainty assessment 'for identifying the robustness of results.' They demonstrate the tool using a case study of residential windows. However in the case study, they do not make use of the Monte-Carlo analysis function, but instead use a form of scenario analysis to compare the effects varying different input parameters and model assumptions. They present LCA results for five different window types and for three different locations in the United States. The graphical format of their results does not allow the data to be accurately interpreted but changing the frame type from aluminium to PVC appears to reduce the GWP of the window by approximately 20%.

Acquaye et al. (2011; 2011) and Aktas and Bilec (2012) also used Monte-Carlo analysis to assess uncertainty. The studies presented by Acquaye et al. are sectoral assessments of embodied carbon in

Irish residential construction. The uncertainty in embodied carbon factors for concrete, steel, insulation, timber and brick are modelled statistically using data from the Inventory of Carbon and Energy (Hammond & Jones, 2011). The authors argue that the use of stochastic modelling such as Monte-Carlo simulation can provide 'more useful information to building designers and policy makers.' (p. 1302). However, their study does not investigate the underlying sources of uncertainty in the embodied carbon factors of materials. Therefore, whilst the results communicate the magnitude of uncertainty, they do not show its cause. This may have some value for further modelling of the effects of policy decisions at the sectoral level but it is not clear how a building designer could make use of the results to inform design decisions.

A similar criticism can be levelled at the results presented by Aktas and Bilec (2012). They base their distributions for the embodied carbon of different interior finishes on data points extracted from literature and from the SimaPro (2015) LCA software without investigating further what causes this variation. They note that the data for deriving distributions for embodied carbon of materials are sparse and this led them to use uniform or triangular distributions for these parameters.

Other studies reviewed used variations of scenario analysis to assess the effects of uncertainty. Peuportier (2001) investigated how different transport distances and levels of insulation affect the LCA results for single-family dwellings in France, finding that the changes were very small at just 1-2% difference from the initial result. The study also included an investigation of the effect of different assumptions about the end of life processing of the buildings. It was found that incinerating timber in the building instead of sending it to landfill leads to an 8% increase in GWP. However, the selection of which parameters to test in this way is not clearly justified and the author does not draw conclusions as to which sources of uncertainty are the most significant. Similar approaches using scenario analysis have been applied by Cellura et al (2011), Kua and Wong (2012), Nassen et al. (2012), Peuportier et al (2013), and Vieira and Horvath (2008). In each of these examples, uncertainties about future processes for waste treatment at end of life were assessed. Cellura et al. modelled four different scenarios for the transport, electricity generation and the kiln firing of ceramic tiles. They found that the GWP of the case-study tile varied between -11.6 and +24% of the base scenario. They refer to previous studies and sources of LCA data as a basis for determining the scenarios which were modelled. The study presented by Nassen et al. (2012) included a comparative assessment of wood and concrete framed buildings where the authors found that the results are sensitive to the assumptions made in modelling embodied carbon for each alternative.

In comparison to the studies that use Monte-Carlo simulation, the use of scenario analysis provides a clearer link between a specific source of uncertainty and the effect this has on the results. However, the rationale for selecting which parameters to include in these scenario analyses was not clearly stated in any of the studies reviewed.

2.7.5 Identifying Relevant Sources of Uncertainty

In order to identify the range of different sources of uncertainty that can affect an embodied carbon assessment of a building, the 34 peer reviewed papers which were initially found to make reference to uncertainty were reviewed a second time. Sources of uncertainty mentioned in the discussions were logged to produce an initial list with 33 entries. Related or similar sources given different terms were then grouped together to produce a revised list of 18 sources of uncertainty relevant to embodied carbon assessments of buildings. The 18 sources and the related terms from the initial list of 33 sources of uncertainty are shown in Table 2-4. These lists were sourced from just 28 of the papers, as shown in Table 2-5, whilst the remaining 6 made no specific mention of sources of uncertainty.

Table 2-4: Sources of uncertainty that may affect embodied carbon assessments of buildings identified by systematic literature review (see Table 2-5 for details of papers reviewed)

Source of uncertainty	Other terms in papers reviewed	Descriptions
Allocation	-	Method used to allocate emissions between co-products of one process
Assumptions	-	Assumptions about materials or processes upon which embodied carbon estimates are based
Average vs specific data	-	The difference between data intended to represent industry averages and data intended to represent a specific product or process.
Data quality	Age of data	See discussion of data quality in sections 2.2.3 and 5.3.2.
End of Life	-	Assumptions about the processes used to process materials at the end of their life or the life of the building.
Energy Source	-	The different carbon intensities of alternative fuels (and electricity) that may be used at each stage of the product or building life cycle.
Functional unit	-	Carbon emissions (and other environmental impacts) are assessed for a unit of material or product which is defined in terms of its function. Different functional units can lead to different results.
Geographic variation	-	There is variability in the carbon factor of materials and products between regions due to different production practices and levels of efficiency as well as different carbon intensities for electricity production

Source of uncertainty	Other terms in papers reviewed	Descriptions
Maintenance/refurbishments	-	Different assumptions about the frequency and scope of maintenance and refurbishment.
Measurement error	-	Equipment and techniques used to measure data may be subject to errors
Measurement vs estimation	Use of proxies	Whether data can be directly measured or must be estimated based on measurements of a related parameter or proxy.
Method	-	Different choices about the methods used to estimate embodied carbon. See section 6.2 for analysis and discussion of methodological choices relevant to the materials assessed as part of this research.
Process / technological variation	-	Materials can be made using different processes or techniques which may have different carbon intensities.
Recycling rates	-	The percentage of material that is assumed to be recoverable for recycling at the end of its life
Service life length	-	The period in which a product or a building is in use at the end of which it is disposed of or demolished
Specification	Product alternatives Specification	Where a material or product is not specified in full detail and assumptions must be made in order to estimate its embodied carbon
System boundary	System boundary Exclusions / cut-offs Capital equipment Primary vs delivered energy	See definition of system boundary in section 5.3.1.2.2
Time horizon of emissions	Time horizon of emissions	The period during which the GWP of GHG emissions to the atmosphere is assessed
Transport	Transport	Different assumptions about distance, vehicle type and vehicle load

The details of which sources of uncertainty were discussed in each of the 28 papers included in this review are shown in Table 2-5 below.

Table 2-5: Sources of uncertainty discussed or assessed in peer reviewed journal papers on embodied carbon or LCA of buildings and construction materials

Paper No. (see references below)	Allocation	Assumptions	Average vs specific data	Data quality	End of Life	Energy Source	Functional unit	Geographic representativeness	Maintenance/refurbishments	Measurement error	Method	Process / technological variation	Recycling rates	Service life length	Specification	System boundary	Time horizon of emissions	Transport
1			●	●						●		●						
2			●	●						●		●						
3														●				
4						●		●			●	●			●			
5															●			
6				●	●	●								●				
7	●			●				●			●	●				●		
8				●				●				●						
9												●						
10				●				●				●						
11				●				●				●						
12	●	●			●		●	●		●			●			●	●	
13														●				
14																●		●
15				●								●						
16		●																
17		●		●														
18				●														
19																		
20					●										●			
21							●											
22	●	●														●		
23				●	●	●		●						●				
24									●					●				
25				●														
26				●								●						
27	●				●							●						
28				●		●					●	●				●		
Totals	**5**	**5**	**2**	**15**	**5**	**4**	**2**	**7**	**1**	**3**	**4**	**12**	**1**	**5**	**3**	**6**	**1**	**1**

1 Acquaye et al. (2011); 2 Acquaye et al.(2011); 3 Aktas and Bilec (2012); 4 Aye et al. (2012); 5 Blengini (2009); 6 Bribian et al. (2011); 7 Cellura et al. (2011); 8 Ciroth et al. (2013); 9 Van Geem and Marceau (2006); 10 Gong et al. (2012); 11 Van den Heede and De Belie **(2012)**; 12 Huijbregts et al. (2003); 13 Joensson et al. (1997); 14 Kellenberger and Althuas (2009); 15 Kofoworola and Gheewala (2009); 16 Kua and Wong (2012); 17 Van der Lugt et al (2006); 18 Monahan and Powell (2011); 19 Mosteiro-Romero et al 2014(2014); 20 Nassen et al (2012); 21 Norman (2006); 22 Norris and Yost (2001); 23 Peuportier (2001); 24 Peuportier et al (2013); 25 Proietti et al (2013); 26 Scheuer et al (2003); 27 Vieira and Horvath (2008); 28 Yohanis and Norton (2002)

The data in Table 2-5 show that the most widely acknowledged and discussed sources of uncertainty are data quality and technical variations in production processes. However, the results presented in the fourteen papers which include a form of uncertainty assessment do not provide adequate detail to determine if these two sources are also the most important in terms of the magnitude of uncertainty that they introduce to embodied carbon results for a building or a construction product or material. Moreover, the list in this form does not show how these sources of uncertainty relate to the dimensions of uncertainty defined by Walker et al. (2003) in their uncertainty typology. Indeed, categorising sources of uncertainty according to a typology can inform selection of the most appropriate uncertainty assessment methods (Van der Sluijs et al., 2004) an approach that has been used for this research (see sections 3.4.1 and 5.3.1).

2.8 Summary of Key Outcomes from Literature Review

The following key conclusions drawn from the literature have shaped the subsequent research design set out in Chapter 3:

- Process based embodied carbon assessment methods provide valid and useful insights to quantify and reduce the impact of the built environment on climate change (section 2.3)
- BIM is seen by some as a useful source of material quantity data for conducting LCA and LCA related methods such as embodied carbon assessments (section 2.6)
- Tools have been developed to exploit the data generation capabilities of BIM for the purpose of LCA and embodied carbon assessments. But this approach is relatively new and how suitable BIM data are for this purpose and how best to link BIM data and carbon factor data requires further exploration.
- However an apparent lack of comparability of results between studies is viewed as problematic. This is generally acknowledged to be due to variations in methods and data used (section 2.2)
- The availability of carbon factor data at the product level has been highlighted as a cause of variation. Six different sources of carbon factors were identified (section 2.4):
    1. Factors derived/aggregated from literature review
    2. Industry data – e.g. carbon factors provided by a product supplier or industry body but which are not published as part of a formal environmental declaration (see below)
    3. Government data – generic carbon factors provided by national governments, such as those released by Defra (2015) for use by UK organisations compiling annual carbon emission reports

4. Factor from a commercial LCA database such as GaBi or Ecoinvent
5. Factor from a PAS 2050 compliant carbon footprint
6. Factor from an EPD (EN 15804 compliant)

- The increased availability of EPDs based on the European standards is seen by some authors as having the potential to improve comparability and reduce the variability of embodied carbon results for buildings (section 2.3.3)
- Despite the perceived lack of comparability and the acknowledgement of uncertainty about the outcomes of embodied carbon assessments, formal uncertainty assessment was only applied in a quarter of studies reviewed (section 2.7.4).
- The studies of embodied carbon or LCA of buildings where uncertainty assessments were conducted lack a comprehensive review of the relevant sources of uncertainty (section 2.7.5)
- The methods applied are predominantly quantitative and where the scope of the uncertainty assessment has been restricted to selected parameters or scenarios, the justification for their selection is unclear (section 2.7.4).

3 Research Methods

This chapter describes and discusses the research strategy which was developed to achieve the aim and objectives detailed in the introduction, and the methods adopted. Reflecting on the insights and conclusions from the literature review in the previous chapter, the methods set out here draw on and build upon theoretical and empirical research from fields relevant to embodied carbon assessment and uncertainty. The methods for embodied carbon assessment and uncertainty assessment each draw from different fields of research, albeit with some links and common themes. Embodied carbon assessment methods are derived from the field of LCA, which is a form of environmental modelling that:

> Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave). (British Standards Institution, 2006a, p. v)

Uncertainty assessment methods have developed in a number of areas relating to environmental modelling such as climate modelling, environmental impact modelling and health impact assessments as well as LCA (Ciroth et al., 2013; Slottje, van der Sluijs, & Knol, 2008; Van der Sluijs, Risbey, & Ravetz, 2005; Krayer von Krauss, Casman, & Small, 2004). This chapter provides an overview of how embodied carbon assessment and uncertainty assessment are applied in this research to support the achievement of the research aim. The methodological rationale underpinning the research is first outlined, followed by a summary of the research design. The methods for integrating BIM and embodied carbon assessment are summarized in section 3.4. This is followed by an overview of the uncertainty assessment method in section 3.5. Further details of these methods along with results are then provided in Chapters 4 and 5-7 which focus on embodied carbon assessment and uncertainty assessment respectively.

3.1 Research Position

Sainsbury's objective to quantify and reduce the embodied carbon of its buildings is a key driver for this research. The extant literature shows broad consensus that such an undertaking requires the use of quantitative analysis methods rooted in positivism (Darby, 2014; Tukker, 2000). In order for the research to deliver outcomes that can be applied to the problem and context which Sainsbury's seeks to address, the work follows and builds on this empirical, positivist tradition. Such methods are characterised by, amongst others, a 'focus on deduction, confirmation, […] prediction, standardized data collection, and statistical analysis' (Johnson & Onwuegbuzie, 2004, p. 18).

However the literature review has also highlighted the subjective nature of uncertainty. Van Asselt and Rotmans assert 'that a pluralistic approach to uncertainty is needed to comply with the social scientific evidence that different interpretations of uncertainty and different risk perceptions are legitimate.' (2002, p. 76). In seeking to understand the role of uncertainty in embodied carbon assessments it is therefore necessary to engage with concepts, ideas and methods from social scientific research fields. It has been argued that the paradigms on which qualitative and quantitative research are founded are conflicting (Guba, 1990). However Johnson and Onwuegbuzie 'reject an incompatibilist, either/or approach to paradigm selection [and] recommend a more pluralistic or compatibilist approach' (2004, p. 17). Hence the research proceeds on the basis that a degree of methodological pluralism has the potential to provide valuable insights which a purely positivist approach might fail to reveal (Dainty, 2008; Norgaard, 1989).

3.2 Research Design

The research aim is to propose and demonstrate a method for estimating embodied carbon of supermarket buildings during the design stage, taking account of uncertainty and evaluating how this affects the use of such estimates in decision making.

And the objectives set in support of this aim are to:

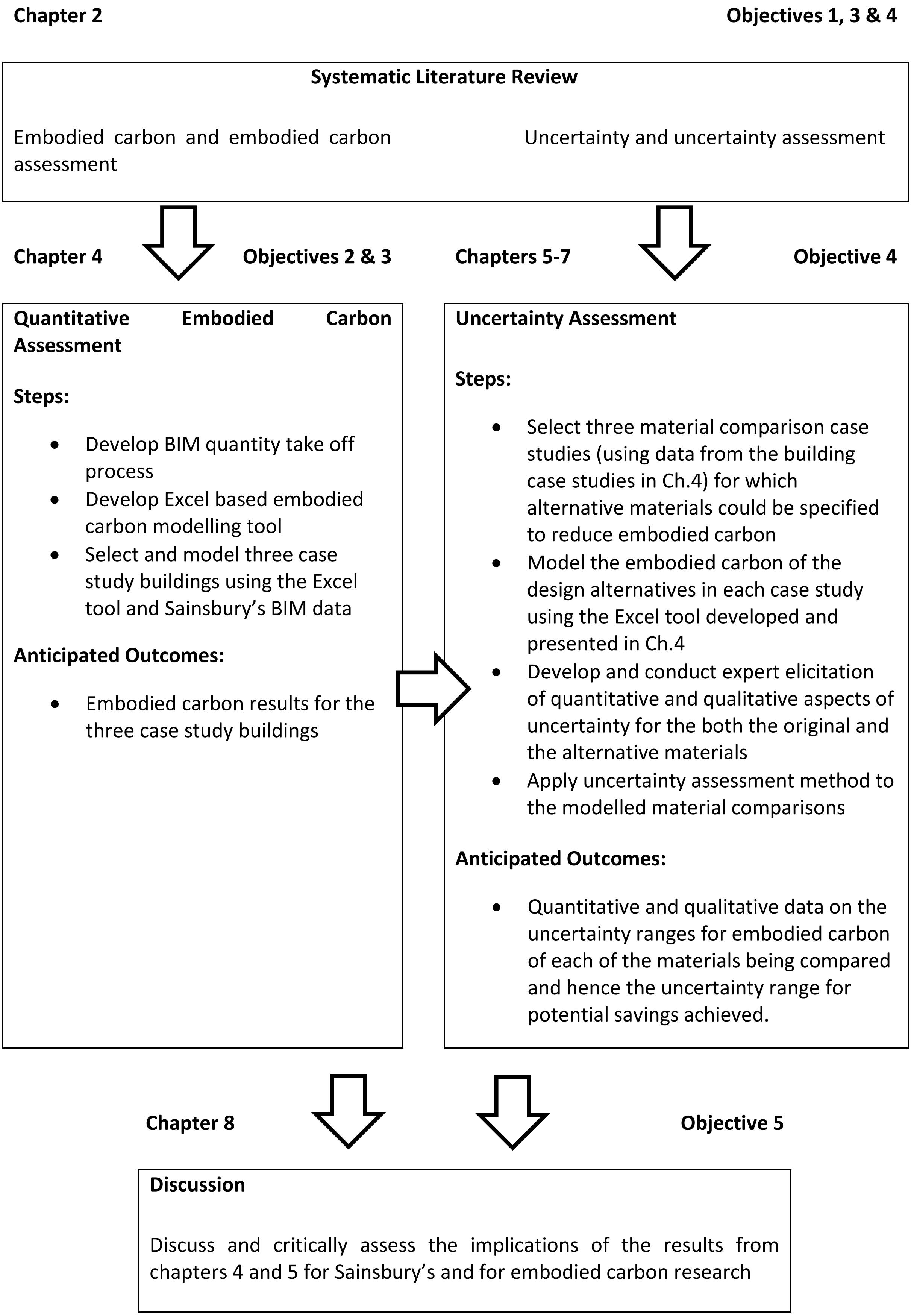
1. Identify suitable sources of data for use in the estimation of embodied carbon in supermarket construction and evaluate their usefulness for Sainsbury's.
2. Evaluate the potential to automatically generate material quantities data that are appropriate for embodied carbon assessments using Sainsbury's BIM models, and to make recommendations for their improvement.
3. Develop and demonstrate a new approach for estimating embodied carbon of supermarket construction on the basis of 1 and 2 above.
4. Investigate the nature and potential impact of uncertainty in estimating embodied carbon, and evaluate current approaches for assessing it.
5. Develop and demonstrate an approach to incorporating uncertainty assessment into the estimation of embodied carbon at 3 above to show the effect uncertainty can have on design decisions to reduce embodied carbon.
6. Examine how embodied carbon assessment results produced using this new approach can support Sainsbury's aim of reducing its climate change impacts.

Since the primary aim of the research is to evaluate embodied carbon in supermarket construction, a case-based approach (Yin, 2013) was adopted using supermarket stores identified in conjunction with

Sainsbury's as reflecting a broad range of those currently being constructed. The case study buildings are then used as the basis for the quantitative modelling of embodied carbon and for the assessment of uncertainty in embodied carbon estimates.

Three supermarket buildings were chosen to serve as case studies. The embodied carbon of each building is assessed using a prototype tool developed as part of the research. In the remainder of the thesis this first set of case studies are referred to as building case studies. For the uncertainty assessment, a further three case studies were selected. This second set of case studies involves comparative assessments of the embodied carbon of two design alternatives, such as might be used to support decision making to reduce the embodied carbon of a building at design stage. These material comparison case studies use material quantity data from the previously assessed building case studies. The uncertainty assessment method developed for the research is applied to each case study to analyse the effects of uncertainty on the comparison of the embodied carbon of the two alternatives. In other words, these case studies serve to illustrate how uncertainty in the embodied carbon of individual materials is compounded when comparing two or more materials and how this in turn introduces uncertainty into design decisions to reduce embodied carbon. The second set of case studies are referred to throughout the thesis as material comparison case studies to differentiate them from the building case studies.

The figure below illustrates how these different approaches are connected and the key outcomes of each, cross referencing these to the relevant chapters and the research objectives that they support. The more detailed methods are described in the sub-sections following.



Chapter 2 **Objectives 1, 3 & 4**

Systematic Literature Review

Embodied carbon and embodied carbon assessment

Uncertainty and uncertainty assessment

Chapter 4 **Objectives 2 & 3**

Quantitative Embodied Carbon Assessment

Steps:

- Develop BIM quantity take off process
- Develop Excel based embodied carbon modelling tool
- Select and model three case study buildings using the Excel tool and Sainsbury's BIM data

Anticipated Outcomes:

- Embodied carbon results for the three case study buildings

Chapters 5-7 **Objective 4**

Uncertainty Assessment

Steps:

- Select three material comparison case studies (using data from the building case studies in Ch.4) for which alternative materials could be specified to reduce embodied carbon
- Model the embodied carbon of the design alternatives in each case study using the Excel tool developed and presented in Ch.4
- Develop and conduct expert elicitation of quantitative and qualitative aspects of uncertainty for the both the original and the alternative materials
- Apply uncertainty assessment method to the modelled material comparisons

Anticipated Outcomes:

- Quantitative and qualitative data on the uncertainty ranges for embodied carbon of each of the materials being compared and hence the uncertainty range for potential savings achieved.

Chapter 8 **Objective 5**

Discussion

Discuss and critically assess the implications of the results from chapters 4 and 5 for Sainsbury's and for embodied carbon research

Figure 3-1: The elements of the research design and the key research objectives that each relates to

Figure 3-1 shows that the research commenced with a detailed review of the relevant literature. In addition to providing a discursive critical assessment of prior work in this field, a systematic approach was adopted in order to deliver two key outcomes. The first of these outcomes was the identification and analysis of different sources of data that have been used for conducting the quantitative embodied carbon assessments. This provides the basis for assessing the suitability of these data sources for this research and the specific context of embodied carbon assessments of supermarkets, thus supporting the fulfilment of objective 1. The second outcome of the systematic literature review was the identification of sources of uncertainty affecting embodied carbon assessments. These provide the basis from which the uncertainty assessment detailed in chapters 5-7 progressed.

Two sets of case studies were conducted. The first set, the building case studies, comprised three supermarket building designs and the quantitative modelling of the embodied carbon of each. The application of the modelling method to these building case studies, and the results produced fulfil objective 3. The critical analysis of both the inputs to and outputs from the model allows for conclusions to be drawn in fulfilment of objectives 1 and 2. The buildings selected for the building case studies each represent typical configurations that have been used by Sainsbury’s in recently constructed supermarkets. This ensures that the case study results have wider relevance for Sainsbury’s design considerations since comparisons can be made between the embodied carbon of each alternative configuration. The embodied carbon assessment method is described in greater detail in section 3.3. Further specific details of the selected buildings, and the results and discussion of the building case studies are presented in Chapter 4 and these support the fulfilment of objectives 2 and 3.

The second set, the material comparison case studies, involves using the model to compare embodied carbon of different design alternatives for a particular element of a building. Three case studies are carried out, each comparing a different set of alternative materials designed to fulfil a similar function in the building. The first is the comparison of two materials for the structural frame, the second is the comparison of two composite roof systems and the third compares different types of concrete for the floor slab. In these case studies, the scope of the embodied carbon assessment is limited to specified function and all other parts of the building are excluded to allow direct comparison of the embodied carbon of the design alternatives.

Each of the material comparisons represents a typical example of material substitution that Sainsbury’s has used in recently constructed supermarkets and which was estimated at the time, by Sainsbury’s or its consultants, to have reduced the embodied carbon of the building. The uncertainty in the carbon factors for each material included in these case studies is assessed and this is then used to evaluate the resultant uncertainty in the estimated reduction or increase in embodied carbon that is achieved by substituting one design alternative for another. Details of the methods used to determine the uncertainty of inputs to the material comparison case studies are presented in section 3.4 and also in Chapters 5 and 6. The analysis of the material comparison case study results is presented in Chapter 7 and fulfils objective 4.

Finally, objective 5 is fulfilled in the form of a discursive analysis of the combined outcomes from both sets of case studies (building and material comparisons) and the methods and data upon which they are founded. This discussion is contained in Chapter 8.

3.3 Embodied Carbon Assessment Method

In the literature review in Chapter 2, three methods of embodied carbon assessment were identified and described, namely process analysis, EEIO, and hybrid assessments. Process analysis is the method that has been adopted within European standards for assessing the environmental sustainability of buildings and construction products (British Standards Institution, 2014a, 2011a). These standards are frequently cited and applied in the academic literature as well as industry publications. Moreover, there is evidence of increasing uptake, amongst suppliers of construction products, of the EN 15804 method of producing EPDs (see section 2.4.6). Sainsbury's approach to carbon assessment to date has been to work with existing reporting standards (J Sainsbury plc, 2015; Deloitte, 2010), and there is a desire to maintain this alignment with wider industry practice as well as a desire to make use of existing and future EPD data. Furthermore, the literature shows that there is a lack of consensus as to whether the use of EEIO or hybrid methods can improve the robustness of an embodied carbon assessment compared to using only process analysis (see section 2.1.3).

There is therefore a strong case for applying the methods set out in EN 15978 in this research. These methods will allow more meaningful comparison with results from other studies that follow the same approach. The standards introduce a 'modularity principle', to define the scope and boundaries of a study by dividing the building life cycle into four modules, labelled A-D. The definition of these modules and the corresponding sub-modules can be seen in Figure 2-3 on page 17. By adopting this same modularity principle to define which aspects of the life cycle are included in this research, it should make it possible for others researchers and practitioners to draw comparisons between this and other studies and to readily identify the reasons for any discrepancies.

3.3.1 Data Sources: Carbon Factors

In the literature review (section 2.4), six potential sources of carbon factor data were identified. Five of these represent sources of data that has been produced and published by a researcher or an organisation and which can be used directly. These are factors derived/aggregated from literature review, industry data, government data, PAS 2050 carbon footprint data, or data from an EPD (EN 15804 compliant). A further source of data identified is commercial LCA software. These allow environmental impacts, such as carbon factors, to be calculated using a built-in LCI database, which can if desired, be supplemented with primary data. These software packages thus offer greater flexibility to adapt or derive carbon factors that are specific to a particular organisation. The possibility of generating a bespoke set of carbon factors for Sainsbury’s using commercial LCA software and an associated database of life cycle impacts (LCI) was considered. Whilst this approach has been applied by other researchers (e.g. Darby, 2014), it was not used here for practical reasons. The desire was to develop an approach to embodied carbon assessment that could be applied by Sainsbury’s without significant cost or the need to draw in external expertise. LCA software and, in particular, the LCI databases they contain apply annual subscription fees, typically several thousand pounds per year for a commercial licence. Moreover the complexity of commercial LCA tools is seen as a barrier to their use in the context of evaluating buildings (Jrade & Abdulla, 2012) and their use requires significant experience and expertise with the software. Hence, this approach would be unlikely to be sustainable for Sainsbury’s in the longer term, beyond the completion of this research. There is support in the embodied carbon literature both for wider availability and increased use of published carbon factors, provided they are produced in accordance with EN 15804 (Moncaster & Symons, 2013).

Whilst the availability of EPD continues to increase, there are still many construction materials and products for which EPD are not available. Furthermore, under EN 15804, only modules A1 (raw material supply), A2 (transport of raw materials) and A3 (manufacture) are mandatory (See Figure 2 3 and British Standards Institution, 2014a). EPDs that only report these mandatory modules are known as cradle-to-gate assessments. Where additional life cycle stages are included this is known as cradle-to-gate with options and finally, the term cradle-to-grave is applied to EPD which include all life cycle modules. Many EPD were identified in the course of this research which only report cradle-to-gate emissions. It was therefore anticipated that based on current availability, it would not be possible to obtain all the carbon factors required for this research from EPD. A rational and justifiable basis for deciding what additional sources of data to use was therefore required. A data quality matrix (Weidema & Wesnæs, 1996) , also known as a pedigree matrix (Funtowicz & Ravetz, 1990) was utilised to evaluate different sources of carbon factor data according to four criteria affecting their quality. The criteria were adapted from prior work on assessment of data quality in emissions inventories (Risbey, Sluijs, & Ravetz, 2006) and relate to what is measured (and how closely or directly this correlates to the desired parameter), the empirical reliability of the data, the robustness of data acquisition methods, and finally the level of data validation. The use of the data quality matrix involves scoring each data source against the predetermined data quality criteria. In this work, the scoring was undertaken as part of the expert elicitation process which is described in section 3.4.3. Whilst the outcomes have been used to determine the selection of carbon factors for the embodied carbon model and case studies presented in Chapter 4, the explanation of the data quality criteria used, are presented in Chapter 5, and the results in Chapter 6, alongside the other aspects of the expert elicitation process.

3.3.2 Data Sources: Material Quantities

In section 2.5, the approach of EN 15978 and 15804, to quantifying the flows of materials and energy into and out of the building over its life cycle was discussed. Energy flows such as those occurring during construction and demolition are accounted for in the carbon factors of each individual material. This means that only physical flows of material need to be quantified and these are then multiplied by the appropriate carbon factor. The growth in adoption of BIM (McGraw Hill Construction, 2014)and the increasing functionality and sophistication of BIM enabled design software has led several researchers to propose that BIM could provide a means of simplifying the generation of material quantities for conducting embodied carbon assessments or, indeed, LCA (see section 2.6.1). There is support for this in industry too, since at the time of writing a number of tools for conducting BIM based embodied carbon assessments of LCA are in the early stages of commercialisation (see following section and Table 3-1).

3.3.3 Software Evaluation

When this research began in 2012/13, a review was undertaken to identify software tools that could be used to conduct embodied carbon assessments. Several other published studies have reviewed available tools either for embodied carbon assessments or LCA of buildings (Cabeza et al., 2014; Moncaster & Song, 2012; Norris & Yost, 2001). Therefore, the focus here was to identify those tools which offered capability to conduct embodied carbon assessments using BIM to generate materials quantities. Based on the results of the literature review, the research design, and discussions with Sainsbury's staff, the following factors were considered in evaluating the suitability of embodied carbon assessment tools:

1. Compliance with EN 15978 life cycle modules
2. Availability of integral (EN15804 compliant) carbon factor data
3. Possibility for the user to modify or update carbon factor data
4. Transparency of results – i.e. to what extent can they be interrogated

5. Compatibility with Sainsbury's existing BIM software tools
6. Stage of development
7. Cost of implementation

The following tools were identified which were understood to have been developed to provide some level of BIM-integration:

3.3.3.1 Tally

Developed by US firm *KT Innovations* and Autodesk and using data provided by *PE International* (now *thinkstep*), this plug-in for Revit claims to allow LCA of the building's materials to be carried out directly during the design development (KT Innovations, 2016). Revit (Autodesk, 2014) is one of the market leading digital design tools for architects and plug-ins are additional software packages, often provided by third parties, which can be installed to give Revit increased functionality. Once installed and activated, the *Tally* plug-in analyses the Revit model and takes the user through a process of assigning material profiles to each element of the model. These material profiles contain the environmental impact data from which LCA results are calculated. The material selections available to the user for each element are tailored to match the data that *Tally* has extracted. For instance, Tally identifies a wall in the model and presents the user with options for the wall's construction, such as types of masonry, insulation, and internal and external finishes, based on the detail available in the model. Once the user has specified or confirmed the materials for each element of the building, *Tally* presents an estimate of the environmental impacts of the building for a number of impact categories which include GWP or carbon emissions. The tally results are presented as a printable report and a spreadsheet of the underlying data which can be edited. The environmental impact data used in *Tally* are based on *thinkstep's* GaBi database and are US specific. There is currently no possibility for the user to override this using other data (KT Innovations, 2016).

3.3.3.2 IMPACT

The UK based companies, BRE and IES developed IMPACT (Integrated Material Profile and Costing Tool) as part of a Technology Strategy Board (TSB - now InnovateUK) funded project with a number of other partners. The IMPACT method and data is made available to software developers by BRE, allowing for LCAs of building materials to be conducted by using their software (BRE Group). In 2013, only IES had developed IMPACT compliant LCA capability within their *IES-VE* software package. The primary function of this software is thermal simulation and energy modelling of buildings. The three dimensional model of the building in IES-VE is used to estimate material quantities which are then used by the IMPACT software to conduct LCA based on BRE environmental impact data. These data are UK specific, but cannot be changed or updated by the user. The tool offers BIM integration in so far as the IES-VE software can import Revit models. The process for conducting an assessment is broadly comparable to that adopted by Tally. The user must assign the relevant material environmental profile to each part of the building. The main practical difference is the need to conduct the assessment in IES-VE rather than in Revit.

At the time of writing, the Australian based *eTool* platform is the only other licenced provider of IMPACT compliant LCA, however *eTool* does not currently offer integration with BIM software and so material quantities must be entered manually using an online form (eTool, 2014).

3.3.3.3 iCIM

The Inter-operable Carbon Information Modelling (iCIM) tool was also developed as a collaborative project with TSB funding. It is a web-based platform which allows industry foundation class (IFC) files (an industry standard BIM file format) exported from a BIM enabled design package to be uploaded. The tool uses the IFC data to generate material quantities and hence calculate the embodied carbon. Carbon factors for materials are based on the Inventory of Carbon and Energy (Hammond & Jones, 2011). There is no evidence that further development is taking place and websites relating to the tool have not been updated since 2012 (OpenBIM, 2012). All attempts to contact the developers to request a trial of the tool were unsuccessful.

3.3.3.4 CombiCycle

CombiCycle is a web-based tool intended to perform both LCA and life cycle costing. It was developed privately by Williams and Lay and is currently owned by IFPI ltd (2011). Little information is provided in the CombiCycle website as to the specific features and capabilities of the software (IFPI, 2011). The information used for assessing CombiCycle for this research was obtained during a face-to-face meeting with the developers at Sainsbury’s offices in 2013. From that meeting, it was determined that much of the data entry was manual and that embodied carbon calculations were based on carbon factors from the Inventory of Carbon and Energy (Hammond & Jones, 2011). However, at the time a software error had apparently caused the web-platform to crash and so a full demonstration was not possible.

These four tools were evaluated against the seven selection criteria listed above and Table 3-1 shows a summary of the outcomes of this process. It should be noted that this represents the features and capabilities of these tools when they were first considered for use in early 2013.

Table 3-1: Assessment of the functionality of BIM-integrated embodied carbon tools (conducted early 2013)

Criterion	Software/Tool capabilities assessed against the selection criteria			
	Tally	IMPACT/IES-VE	iCIM	CombiCycle
EN 15978 compliance	No: Does not provide full breakdown against life cycle modules and sub-modules	Yes	Not known	No
Integral carbon factors	Yes. But based on US data.	Yes, using BRE methodology	ICE data	ICE data
User carbon factor updates	Not currently possible	No	Not known	Yes
Interrogation of results	Extensive. PDF with multiple charts. Also Excel spreadsheet automatically generated to allow further analysis.	Not known	Not known	Not known
Compatibility with Sainsbury's BIM	Yes. Although breakdown of materials is done using US Construction Specification Institute (CSI) categories	Limited. Assessments must be conducted using IES which is utilised by some of Sainsbury's M&E consultants. Sainsbury's do not have IES licences internally	Yes but further testing would be necessary. Tool uses IFC files which most BIM software is capable of exporting. However some loss of data may occur.	Not known
Development Stage	Commercially available	Commercially available	Not available and no published plans for commercialisation	Not available and no published plans for commercialisation
Cost	$695 per licence per year	Varies depending on functions	N/A	N/A

3.3.4 Software Implementation for BIM-based Embodied Carbon Assessment

On the evidence presented in Table 3-1, it was concluded that none of the software tools assessed was suitable for meeting the objectives of this research. Tally and IMPACT were the only tools at a suitable stage of development and both have significant drawbacks. Tally uses US data and neither Tally nor IMPACT allows the user to override the integrated environmental impact datasets. Hence it would not be possible to add selected EPD data to either tool. It was therefore determined that a bespoke calculation tool would be developed as part of the research. There are several advantages of taking this approach. Firstly, there is complete transparency about how the tool works, what equations, data and assumptions it relies on. Secondly, the results can be interrogated and formatted to suit the needs of the research aims and objectives. This is particularly important for the implementation of the uncertainty assessment, which requires carbon factors to be modified to model different scenarios. Moreover, improved interrogation of the data may well be of value in enabling results to be presented according to Sainsbury's reporting requirements. Thirdly, such a tool can be designed to allow complete flexibility with regard to the use of carbon factors. Finally, the development of such a tool necessitates an examination of different techniques for using BIM to generate material quantities (see section 2.6.1) and the strengths and limitations of each with respect to conducting embodied carbon assessments. The use of an existing software tool would necessarily apply whatever approach to this process has been taken by the software developers. Developing a prototype tool as part of the research generated greater insights in support of objective 2 than might otherwise have been achieved.

The approach of developing 'stand-alone tools' for embodied carbon assessments has been criticised by Ariyaratne and Moncaster for lacking 'the flexibility to be adopted by a wide range of users as well as the efficiency required to be appealing to designers at the early stages of a design (2014, p. 150). They go on to identify three main areas of concern:

> - methods of generating the quantities required to carry out the calculations,
> - dealing with the variations associated with a design, and
> - obtaining the latest data available to carry out the analysis.
>
> (Ariyaratne & Moncaster, 2014, p. 154)

However, the authors specifically cite the use of BIM for producing material quantities as a promising means of overcoming some of the limitations of this approach. The results of the BIM-integrated embodied carbon assessments conducted in the course of this research support this perspective. The challenge of obtaining up-to-date data is related to the time and resources required and the potential to mitigate this through developing improved means of linking quantity and carbon factor data is discussed further in section 8.3.1 of the discussion chapter.

Full details of the software implementation developed in this research to carry out BIM-based embodied carbon assessments are given in sections 4.3 and 4.4 of the next chapter.

3.4 Uncertainty Assessment

The research aims to study the effects of uncertainty on embodied carbon assessments during the design stage of the building. One of the main purposes of a design stage embodied carbon assessment is as a decision support tool. The method may be used by designers to identify which elements of the building are responsible for the largest contribution to embodied carbon. They may also evaluate the effect of adopting alternative design options on the embodied carbon of the building. Such assessments can then be used to support the choice of design alternatives to reduce embodied carbon. Uncertainty about the results of the embodied carbon assessment leads to uncertainty in this decision making process.

It is important to recognise that uncertainty is subjective and is viewed differently by different people who have different roles (Heijungs & Huijbregts, 2004). When considering uncertainty assessment methods, it is therefore important to determine the context in which uncertainty is being considered. For Sainsbury's the rationale for this research was primarily to support their efforts to reduce embodied carbon. Therefore, it is the effects of uncertainty on decision making in the design of supermarkets in relation to embodied carbon reduction measures that were of primary interest. To this end, the uncertainty assessment methods that were developed in this research were applied to case study design alternatives selected on the basis that they were expected to reduce embodied carbon. Taking this approach allowed the scope of the uncertainty assessments to be limited to a palette of materials relevant to the material comparison case studies.

Uncertainty assessment is an established technique which 'identifies, analyses and manages uncertainties' (Skinner, 2012, p. 18). The literature review has shown that uncertainty assessment methods have been developed and applied in a range of different fields including environmental modelling. An embodied carbon assessment is a form of environmental modelling.

A model 'is an abstraction of the system of interest' (Walker et al., 2003, p. 7). In this research, the system of interest is a supermarket building, and specifically the greenhouse gas emissions occurring as a result of the construction, maintenance and refurbishment, and ultimate demolition of the building. The system model is defined by mathematical equations (see Equation 2.2) and quantitative inputs. It is not feasible to create a model that exactly represents the real system, but rather the model 'represents a compromise between desired functionality, plausibility, and tractability' (Walker et al., 2003, p. 7). It is this process of compromise and simplification of reality that leads to uncertainty about the outcomes. As has been discussed in the literature review (see section 2.7.1), uncertainty in the outcomes of the model is a consequence of uncertainty in the model formulation.

Van Asselt and Rotmans hold that 'adequate uncertainty treatment implies that uncertainties salient for the decision-making process are identified, characterised and communicated' (2002, p. 78). Similarly, Heijungs and Huijbregts state that:

> 'In dealing with uncertainty, one is faced with problems at three places:
>
> - the input side: where are the uncertainties, and how large are they?
> - the processing side: how do we translate input uncertainties into output uncertainties?
> - the output side: how can we visualize and communicate uncertain results?' (2004, p. 3)

There is clear correlation between Heijungs and Huijbregts' three problems and the identification, characterization and communication steps posited by Van Asselt and Rotmans. These three steps form the basis of the approach applied in this research. Firstly, potential sources of uncertainty were identified and categorised using the uncertainty matrix (see section 2.7.1 of the literature review and Figure 3-3 on page 60 below). The identification step is important for selecting an appropriate method for the subsequent characterisation of uncertainty, since different methods have strengths and weaknesses in terms of the types of uncertainty that they can account for (Van der Sluijs et al., 2004). The sources of uncertainty identified (see section 3.4.1 below) indicated that a combination of quantitative and qualitative techniques is most appropriate. The final step, communication, takes the form of material comparison case studies which have been chosen to illustrate the impact that uncertainty has on specific design stage decisions for reducing embodied carbon. This three step approach and the techniques used at each step are depicted in Figure 3-2 below.

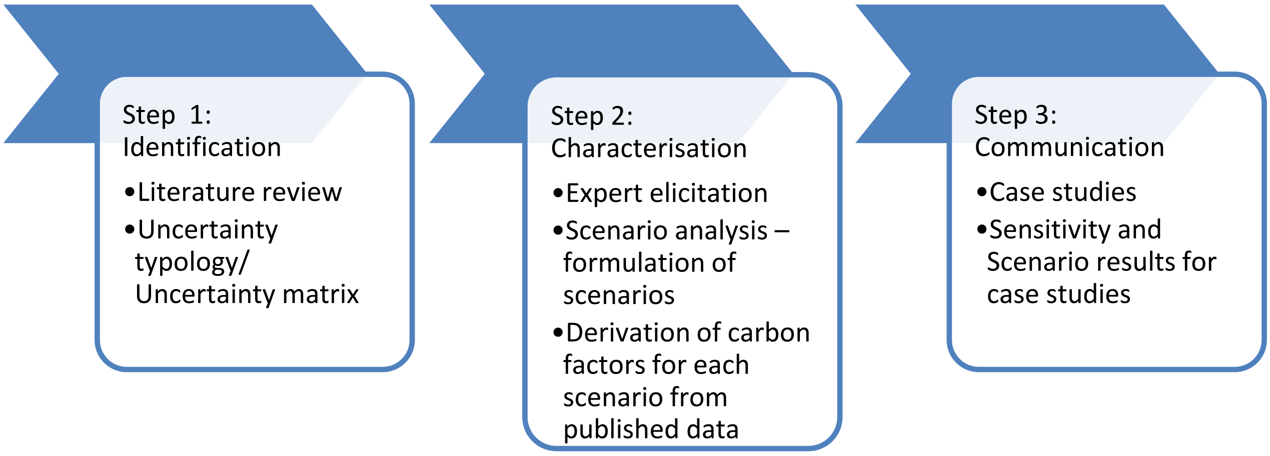


Figure 3-2: Flow chart of the approach to uncertainty assessment applied

The techniques listed in the flow chart for each step are described in further detail in the following sections.

3.4.1 Identifying Sources of Uncertainty

The sources of uncertainty that affect embodied carbon factors were identified through a systematic review of literature on uncertainty in embodied carbon and LCA of buildings. The use of systematic literature review (and related approaches including meta-analysis and literature based discovery) as a research method is widely documented and there are several examples of its use within embodied carbon literature (Pomponi & Moncaster, 2016; Pomponi et al., 2016; Yung, Lam, & Yu, 2013; Dixit et al., 2010). The results of this systematic review are given in Table 2-4 and Table 2-5 in section 2.7.5 of the literature review chapter. The sources of uncertainty identified were then categorized using an uncertainty typology (Skinner, 2012; Huijbregts et al., 2003). A typology proposed by Walker et al. (2003) was adopted which differentiates between three dimensions of uncertainty, namely location, level and nature (see section 2.7.1 of the literature review). Other typologies described in the literature review include elements from some, but not all, of these dimensions. Moreover, Walker et al. also propose the use of an uncertainty matrix which provides a formalised method for the identification process using the three dimensions typology. The uncertainty matrix, an example of which can be seen in Figure 3-3, reflects the three dimensions of uncertainty in the matrix rows (location), columns (level) and sub-columns (nature). The completed uncertainty matrix showing sources of uncertainty identified as relevant to embodied carbon is shown in Chapter 5 (Figure 5-1).

		Level *Nature*			
		Statistical		**Scenario**	
		Epistemic	*Variability*	*Epistemic*	*Variability*
Location	**Model Context**				
	Model Structure				
	Model Inputs				

Figure 3-3: An example of the uncertainty matrix used to categorise sources of uncertainty according to the Walker et al.'s (2003) three dimensions uncertainty typology

3.4.2 Selecting Uncertainty Assessment Methods

The full details and results of the uncertainty identification process can be found in section 5.3.1 of Chapter 5. The resultant uncertainty matrix, which is shown in Figure 5-1 on page 116, was then used as a basis for the further development of the approach and the selection of methods for assessing uncertainty in the embodied carbon factors of materials relevant to the material comparison case studies. The sources of uncertainty identified were found to be spread across the levels of uncertainty in the matrix (statistical, scenario and recognized ignorance).

Statistical uncertainties are those that can be characterised quantitatively (Walker et al., 2003). This characterization may take the form of a range of possible values, for example with maxima and minima (Pomponi, D'Amico, & Moncaster, 2017), or percentage variation relative to a mean value. A probability distribution is a more complex quantitative characterization which provides both the expected range of values that a particular parameter can take as well as the probability that the parameter will be a certain value within the range (Slottje, van der Sluijs, & Knol, 2008).

In the context of embodied carbon, scenario uncertainties are related either to methodological choices or to assumptions about aspects of the product life cycle. They are not readily represented by quantitative ranges (Walker et al., 2003), perhaps because two or more discrete alternatives exist, each of which requires a different set of discrete inputs to the embodied carbon assessment. Quantifying the probability of each option is thus either not possible or very difficult because the data to do so are not available or because the alternatives are not defined by probability but by a normative choice. Such scenario uncertainties cannot be readily assessed using only quantitative techniques and require a combination of qualitative and quantitative methods (Van der Sluijs, Craye, Funtowicz, Kloprogge, Jerry Ravetz, et al., 2005).

In Table 2-1 on page 33, various methods for uncertainty assessment are shown according to the types of uncertainty that they are most applicable for. From the table, it can be seen that the two methods most widely suited to different types of uncertainty are expert elicitation and scenario analysis. Expert elicitation is ‘a structured approach to systematically consult experts on uncertain issues’ (Knol et al., 2010, p. 1) whilst scenario analysis is a method which assesses different possible outcomes based on alternative assumptions about uncertain parameters (Van der Sluijs et al., 2004). Both methods are identified as suitable for assessing scenario uncertainties. Expert elicitation is also recognised as appropriate for assessing statistical uncertainties, and this is usually in combination with quantitative analysis methods (Van der Sluijs, Craye, Funtowicz, Kloprogge, Jerry Ravetz, et al., 2005). Expert elicitation and scenario analysis are also recommended for assessing recognized ignorance. These two methods were therefore selected and developed for the uncertainty assessments conducted in this research.

3.4.3 Expert Elicitation

The US Environmental Protection Agency (2009) suggests a number of factors that can indicate when expert elicitation is an appropriate method to consider. The factors identified that are relevant to this research are:

- Empirical data are not reasonably obtainable; or, the analyses are not practical to perform.
- Uncertainties are large and significant.
- More than one conceptual model can explain, and be consistent with, the available data.

(p. 23)

Generating or obtaining enough empirical data to define uncertainty ranges for material carbon factors using statistical techniques is highly resource intensive (Pomponi, D’Amico, & Moncaster, 2017) and requires access to data that may be commercially sensitive. To obtain this data for the even a small sample of materials in a single building would be impractical in the context of most assessments undertaken for, or by, commercial organisations such as Sainsbury’s. On the evidence of the large variability in published embodied carbon studies of buildings (Moncaster & Song, 2012) and carbon factors of materials (Darby, 2014; Hammond & Jones, 2008), the uncertainties are expected to be significant. Furthermore, it is argued here that the some of the sources of scenario uncertainty that affect embodied carbon factors (discussed in the preceding section, 3.4.2, and in greater detail in section 5.3.1.2) arise because 'more than one conceptual model […] can be consistent with the data' (U.S. Environmental Protection Agency, 2009, p. 23). Expert elicitation is therefore considered to be an appropriate uncertainty assessment method in the context of this research.

Two key principles were central to the development of the expert elicitation method for this research. Firstly, the validity, transparency and reproducibility of the outcomes is increased through the design and execution of a systematic elicitation protocol (Knol et al., 2010). The second is that the elicitation procedure is an iterative rather than a linear process (Knol et al., 2010).

Hence, two sets of expert elicitations were planned. The first set involved a group elicitation with multiple experts in attendance. The purpose of this was to explore different experts' perspectives on uncertainty and to test an initial elicitation protocol which could then be refined for the second set of elicitations. The second set of elicitations comprised a series of semi-structured interviews conducted with experts on an individual basis. The procedure for both sets of elicitations, including identification and selection of experts, and the elicitation format and protocol, is detailed in section 5.3.3 of chapter 5 and was based on that proposed by Slottje et al. (2008) and further developed by Knol et al. (2010). Knol et al. propose a procedure for formal expert elicitations which begins with identifying uncertainties in order to then define an appropriate format, scope and detailed protocol for the elicitations, and select suitable experts. This is followed by preparation and conducting of the elicitations and then finally aggregating and reporting the outcomes.

3.4.4 Scenario Analysis

Scenario analysis is a technique for modelling alternative outcomes. It does not require complex statistical mathematics (Van der Sluijs et al., 2004) which, it is argued here, makes it more appropriate for application in industry than other common quantitative techniques such as Monte Carlo simulation or other Bayesian approaches. These require specialist statistical and programming expertise and are viewed as too complex by many in the industry (Moncaster & Pomponi, 2016). Scenario analysis has the further benefits of clearly communicating both the quantitative range of uncertainty in the results as well as the qualitative information about what affects that range. The scenarios modelled were defined for each of the materials relevant to the material comparison case studies and were based on the outcomes of the expert elicitations. For each material, key assumptions and methodological choices affecting the embodied carbon factor were identified. Each combination of possible choices or assumptions represented one scenario.

3.4.5 Derivation of Carbon Factors for Scenario Analyses

The scenarios identified in the elicitations were then modelled by identifying or deriving carbon factors to represent the relevant set of assumptions or methods. These carbon factors were sought from existing data sources. Full details of this procedure are given in section 5.3.3.2 of Chapter 5 and section 6.2 of Chapter 6.

3.4.6 Material Comparison Case Studies

Each case study involved the comparative assessment of the embodied carbon of two design alternatives to deliver the same function. Thus the goal was to determine which design alternative has the lowest embodied carbon over its life cycle. In each case study, the scope of the assessment is limited to the elements or materials that perform the function for which an alternative design is being considered. For simplicity and clarity all other parts of the building were omitted. The assessment scope was cradle-to-grave, covering modules A1-3 (product manufacture), A4-5 (construction stage) B1-5 (maintenance and refurbishment), C1-4 (demolition and disposal) and D (benefits beyond the life cycle boundary) set out in EN 15804 (British Standards Institution, 2014a) (see also Figure 2-3).

Three material comparisons were chosen based on design alternatives that Sainsbury’s had previously trialled and assessed as part of prior work on reducing embodied carbon (Deloitte, 2010; dCarbon8, 2008). The material comparison case studies are as follows:

- Steel vs hybrid glulam timber and steel for supermarket frame
- Timber cassette vs steel standing seam roof for supermarket
- Standard vs. low carbon concrete (using cement replacements) for in-situ floor slab

The material quantities for these material comparison case studies were obtained from Sainsbury’s BIM models using the approach developed for this research, detailed in Chapter 4. Scenarios were then modelled in Excel using carbon factors derived from publically available sources and accounting for the uncertainties identified in the expert elicitations. The results of the case studies thus show how these uncertainties affect the estimated reduction (or increase) in embodied carbon that can be achieved by implementing each material substitution. Full details of the case studies and further justification of their selection is given in Chapter 7.

4 BIM-Integrated Embodied Carbon Assessments of Supermarkets

In order for Sainsbury's to be able to set embodied carbon reduction targets and monitor progress against these, they need a ready means of assessing the embodied carbon of each new store as it is being designed. The business has identified embodied carbon assessment as one of the potential benefits that could be achieved through the use of BIM to design new stores. In Chapter 2 it has been shown that there is support in the literature for the view that BIM offers a means to simplify or automate parts of the process of conducting building embodied carbon assessments.

Examples exist of commercially available software tools that are designed to allow the user to perform LCA using a BIM model. A review of the capabilities and functions of these (see section 3.3.3) concluded that they did not provide the necessary functionality for the purposes of this research. They lack flexibility with regard to using different sources of embodied carbon data or editing and updating carbon factors as new data becomes available. Moreover, they do not provide full access to the carbon datasets to allow the level of data interrogation or manipulation required for the uncertainty assessments carried out in Chapters 6 and 7 of this research.

A bespoke, BIM-integrated approach to embodied carbon assessment was developed for the purposes of this research. This supports the research objective to evaluate the potential to automatically generate material quantities data that are appropriate for embodied carbon assessments using Sainsbury's BIM models, and to make recommendations for their improvement.

4.1 Requirements

Preliminary requirements for this approach to embodied carbon assessments using BIM were established based on the outcomes of the literature review and also through a series of discussions with Sainsbury's staff, BIM consultants and contractors. The key requirements were:

- To automate as much of the process of conducting an embodied carbon assessment as possible
- To include a set of suitable embodied carbon factors that can be edited and updated as necessary
- To report results according to EN15804 / 15978 modularity principle (British Standards Institution, 2014a, 2011a)
- To be compatible with the software that Sainsbury's and its consultants and contractors currently use

The approach developed to achieve these requirements is presented in sections 4.3 to 4.4 of this chapter. The approach is then applied to assess three case study supermarket building designs that were developed by Sainsbury's using BIM processes and software packages. The building case studies are briefly introduced here and the full details and results of the assessments are presented and discussed in section 4.5.

4.2 Case study selection

Three case study buildings were chosen for embodied carbon assessment using the BIM-integrated approach developed here. The number of potential building designs suitable to be used as case studies was limited by the relatively recent adoption of BIM by Sainsbury's. Sainsbury's has established standards and processes for its consultants and contractors to use when designing new supermarkets using BIM. These are set out in a document known as the BIM protocol, which was adopted in the financial year 2013/14. Hence only supermarket designs produced since that time were considered for use as building case studies.

A review of Sainsbury's recently constructed supermarkets revealed that the typical variants of the construction and layout included;

- the use of timber or steel for the structural frame;
- the use of timber cassettes or metal deck for the roof;
- the presence or absence of a mezzanine floor above the main sales area;
- whether the store is constructed “on stilts” above the car-park or built at ground level with the car-park adjacent;
- the use of pad or pile foundations.

These typical configurations were used as a basis for selecting buildings to use as case studies. This allows for comparisons to be drawn between the embodied carbon of typical alternative design options. By adopting this approach, the case study results have wider relevance for Sainsbury's design considerations. The three building case studies selected are described in Table 4-1.

Table 4-1: Details of the four case study supermarkets whose embodied carbon was assessed as part of this research

Store	Sales Area	Foundations	Frame	Roof	Mezzanine	‘Store on stilts’	Comments

60k Model Store	60,000 ft^2	Pads	Steel	Composite steel deck			This is a hypothetical store design used as a planning tool by Sainsbury's. Its name refers to the sales area and its construction represents Sainsbury's standard format
Leicester North	81,000 ft^2	Pads	Steel & Glulam	Timber Cassettes			Steel frame to the warehouse and glulam for the sales area
Thanet	74,000 ft^2	Piles	Steel	Composite steel deck	•	•	In-situ reinforced concrete pile foundations

4.3 Quantity Take-Off Method

In order to conduct an embodied carbon assessment, it is necessary to establish a list or inventory of all the inputs and outputs to the product system and multiply these by relevant carbon factors. The product system under study here is an entire supermarket building and hence the inputs are the building materials and components and fuel and electricity consumption for the different stages of the life cycle relevant for embodied carbon (see discussion of life cycle stages in section 2.1). The outputs are the waste products that arise from construction and demolition. BIM offers a possible means to readily generate an inventory of materials since the data are stored in the BIM in digital form.

Extracting material quantities from design documentation is known as a quantity take-off (QTO) and the results of a QTO are called a bill of quantities. In traditional (non-BIM) design, the QTO is undertaken manually by a quantity surveyor. The surveyor reviews the design documentation, which consist of drawings and specifications from the architects and engineers. Details of materials are obtained from the specifications and from notes on the drawings and the quantities are estimated by taking measurements from the drawings. In the early stages of design, QTO is undertaken for the purpose of estimating the cost of the build. Contractors also apply QTO methods when they produce a tender or price for constructing the building and for placing orders of materials once a tender is awarded.

The potential to make QTO more efficient by automatically generating bills of quantities from a BIM model has led to development of tools within BIM software for this purpose.

4.3.1 Software

A number of BIM enabled design packages are available on the market. Sainsbury's and its design consultants utilise Autodesk Revit (Autodesk, 2014) for producing the architectural and structural models of new stores. Designing with BIM, should enable efficient transfer of models from one software platform to another using the industry standard IFC file format. However in practice, it has been shown that migrating models using IFC can lead to loss of detail (Kim et al., 2016). For this reason, the decision was taken here to use software from within the Autodesk family which share common file formats.

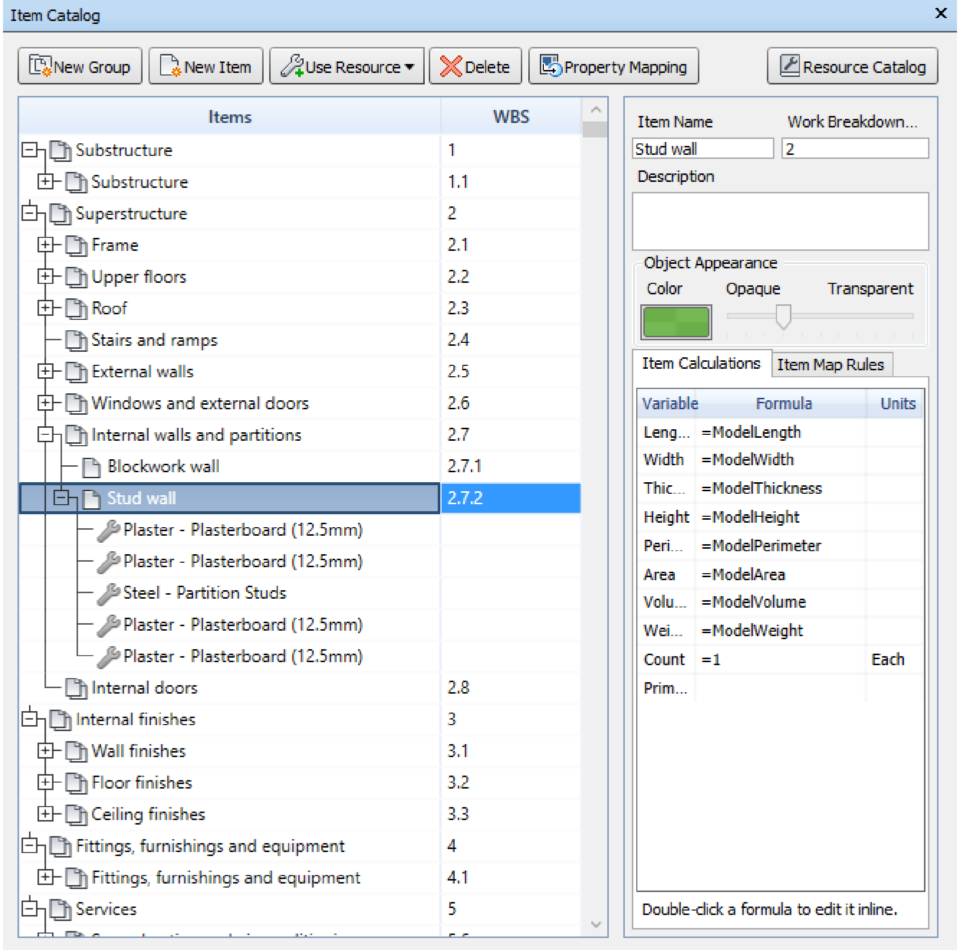
Autodesk Revit has an integral tool for conducting material quantity take-offs. However, through discussions with Sainsbury's BIM consultants and contractors it was established that the functionality of Revit for this purpose is somewhat limited and that Autodesk Navisworks (Autodesk, 2015) is better suited to the task. Navisworks is BIM enabled software aimed at Contractors which facilitates the simultaneous analysis of multiple Revit models and has a more sophisticated set of QTO tools. In particular, Navisworks allows the user undertaking the QTO to include additional materials that are not modelled (Autodesk, 2016). This functionality was useful in overcoming some of the limitations of the building models themselves, which are discussed in section 4.4.3.

4.3.2 Navisworks Quantity Take-Off Procedure

In order to conduct a QTO in Navisworks, it is necessary to specify a quantification catalogue. This is a template or a framework of categories and subcategories into which materials are grouped. These are defined by the user according to their needs. They are commonly used to order the quantity take-off according to standard classification schema such as the New Rules of Measurement (NRM) from the Royal Institute of Chartered Surveyors (2012b). The advantage of the quantification catalogue is that quantities are not simply exported as a single homogeneous list, but are reported according to a hierarchy of groups. Thus, concrete for the foundations can be differentiated from concrete in the superstructure and steel for the frame is distinguishable from steel that is part of the internal fit out, provided the catalogue was set up in such a way and the materials have been assigned to the correct groups during the take-off process. The drawback of this is that it necessitates additional input before the QTO data can be generated and exported. However, without this additional input the quantity data and, hence any subsequent embodied carbon results, would be much harder to interpret

The quantification catalogue comprises two sub-catalogues, the item catalogue and the resource catalogue. When a particular element from the model is 'taken off', the quantities (based on the geometry from the model) are transferred automatically into the item catalogue, into the category specified by the user. The resource catalogue provides a means of assigning additional materials to a given item which are not explicitly modelled. For example, the user may 'take off' a masonry wall and assign this to a category in the item catalogue named external walls. The geometry of the selected wall would be assigned to the external wall category in the items catalogue and automatically added to any other walls already assigned to this item. Assuming the whole wall has been modelled as one element rather than each brick modelled individually, the entry in the item catalogue will only record the overall wall dimensions such as total length, height, depth and volume. In the resource catalogue, an entry can be created for bricks and mortar. This would include formulae for estimating the quantities of these two resources based on the wall geometry recorded in the item catalogue, for example, formulae for the number of bricks or the volume of mortar used per square meter of wall. By assigning these two resources to the masonry wall entry in the item catalogue, the QTO will automatically produce an estimate of the total number of bricks required for all the walls that are taken off to the external walls entry in the item catalogue.

An example view of the item catalogue developed for this research is shown in Figure 4-1 below. The selected item, a stud wall, is contained within the *Internal walls and partitions* category, which is a sub-category of the *Superstructure*. Listed below the highlighted item are the resources that have been assigned to that item. For clarity, Navisworks uses a spanner symbol to indicate resources when viewing the item catalogue. It can be seen that this stud wall has five resources assigned to it, four instances of 12.5mm plasterboard and one instance of steel partition studs.



Items	WBS
Substructure	1
Substructure	1.1
Superstructure	2
Frame	2.1
Upper floors	2.2
Roof	2.3
Stairs and ramps	2.4
External walls	2.5
Windows and external doors	2.6
Internal walls and partitions	2.7
Blockwork wall	2.7.1
Stud wall	2.7.2
Plaster - Plasterboard (12.5mm)	
Plaster - Plasterboard (12.5mm)	
Steel - Partition Studs	
Plaster - Plasterboard (12.5mm)	
Plaster - Plasterboard (12.5mm)	
Internal doors	2.8
Internal finishes	3
Wall finishes	3.1
Floor finishes	3.2
Ceiling finishes	3.3
Fittings, furnishings and equipment	4
Fittings, furnishings and equipment	4.1
Services	5

Item Name: Stud wall

Work Breakdown...: 2

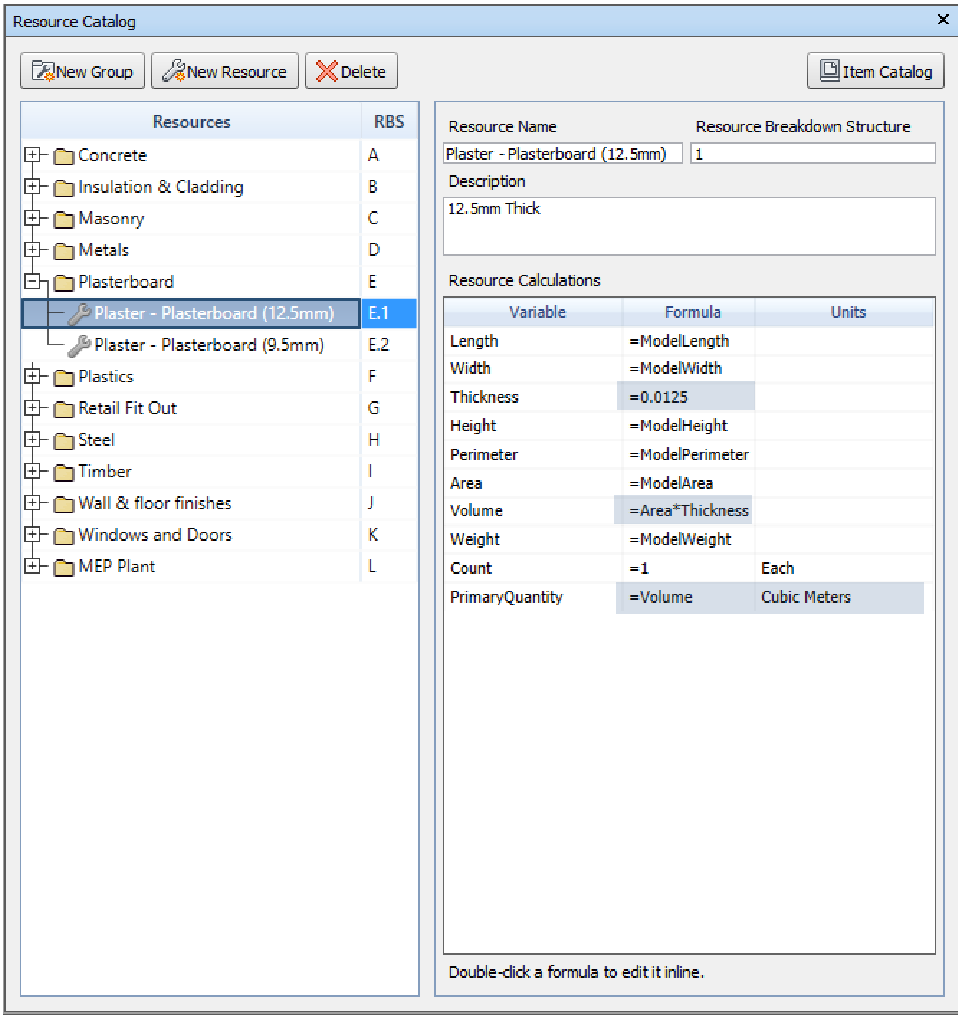
Description:

Variable	Formula	Units
Leng...	=ModelLength	
Width	=ModelWidth	
Thic...	=ModelThickness	
Height	=ModelHeight	
Peri...	=ModelPerimeter	
Area	=ModelArea	
Volu...	=ModelVolume	
Wei...	=ModelWeight	
Count	=1	Each
Prim...		

Double-click a formula to edit it inline.

Figure 4-1: The Navisworks (Autodesk, 2015) *Item Catalogue* interface showing the catalogue defined for this research based on the New Rules of Measurement from the Royal Institute of Chartered Surveyors (2012b).

An example view of the resource catalogue is shown in Figure 4-2 with the entry for plasterboard highlighted that was shown in Figure 4-1 assigned to the stud wall. The cells highlighted in the *Resource Calculations* window on the right hand side show the formulae used for calculating the quantity of plasterboard. By default, all of the parameters in this window are set to equal the equivalent model parameter. This means that for each item where plasterboard is assigned as a resource, Navisworks sets the length of the plasterboard, for example, as equal to the length of that item. For this particular resource, the thickness of the parameter has been overridden with a fixed value of 0.0125 m, which is a common standard thickness of plasterboard. The volume parameter has also been overridden with a formula which multiplies the thickness by the area. The area parameter is equal to the default *ModelArea.* Hence, when this resource is assigned to an item the volume of plasterboard is calculated by multiplying the surface area of that item by 0.0125 m. In the example stud wall shown in Figure 4-1, each side of the wall has two layers of 12.5mm plasterboard and hence this resource was replicated four times for that item.



Resources	RBS
Concrete	A
Insulation & Cladding	B
Masonry	C
Metals	D
Plasterboard	E
Plaster - Plasterboard (12.5mm)	E.1
Plaster - Plasterboard (9.5mm)	E.2
Plastics	F
Retail Fit Out	G
Steel	H
Timber	I
Wall & floor finishes	J
Windows and Doors	K
MEP Plant	L

Resource Name: Plaster - Plasterboard (12.5mm)
Resource Breakdown Structure: 1
Description: 12.5mm Thick

Resource Calculations

Variable	Formula	Units
Length	=ModelLength	
Width	=ModelWidth	
Thickness	=0.0125	
Height	=ModelHeight	
Perimeter	=ModelPerimeter	
Area	=ModelArea	
Volume	=Area*Thickness	
Weight	=ModelWeight	
Count	=1	Each
PrimaryQuantity	=Volume	Cubic Meters

Double-click a formula to edit it inline.

Figure 4-2: The Navisworks (Autodesk, 2015) *Resource Catalogue* interface showing the resource categories defined for this research.

Once both the item catalogue and the resource catalogue have been defined, the user then starts to assign objects within the model to the different categories in the item catalogue. It is this step in which material quantities data are generated. There are two main mechanisms for carrying out this operation within the software. Firstly, the user can 'take-off' components or building elements visually by clicking on an object, such as a wall or a beam, in the graphical workspace and selecting the relevant menu options. All instances of that particular object within the model will then be assigned to the selected category in the item catalogue. There is also a "selection tree" window which lists all of the objects within the model grouped according to the original Revit layers[4]. Here the user can select objects based on their Revit family[5] names and then assign them to the relevant category in the quantification catalogue. The images below in Figure 4-3 and Figure 4-4 show the graphical workspace and the selection tree with the same glulam structural column selected in both.

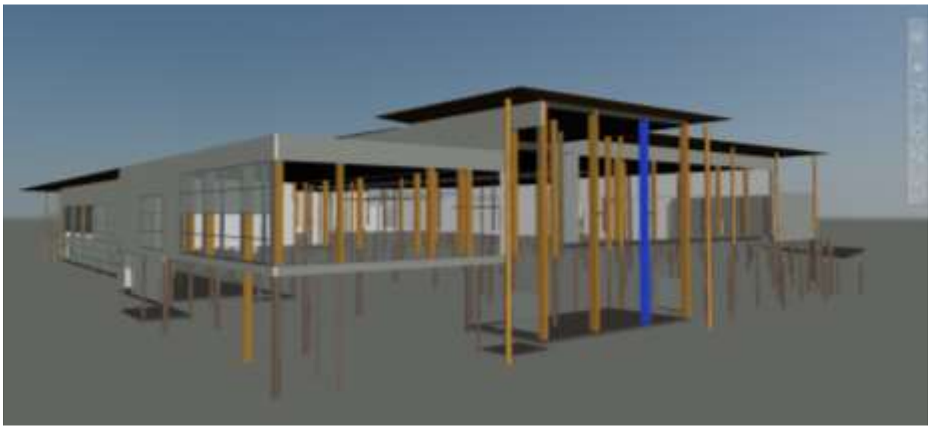


Figure 4-3: The Navisworks graphical workspace with an example of a Sainsbury's supermarket model. The selected glulam structural column (highlighted blue) is the same item as is selected in the selection tree in Figure 4-4

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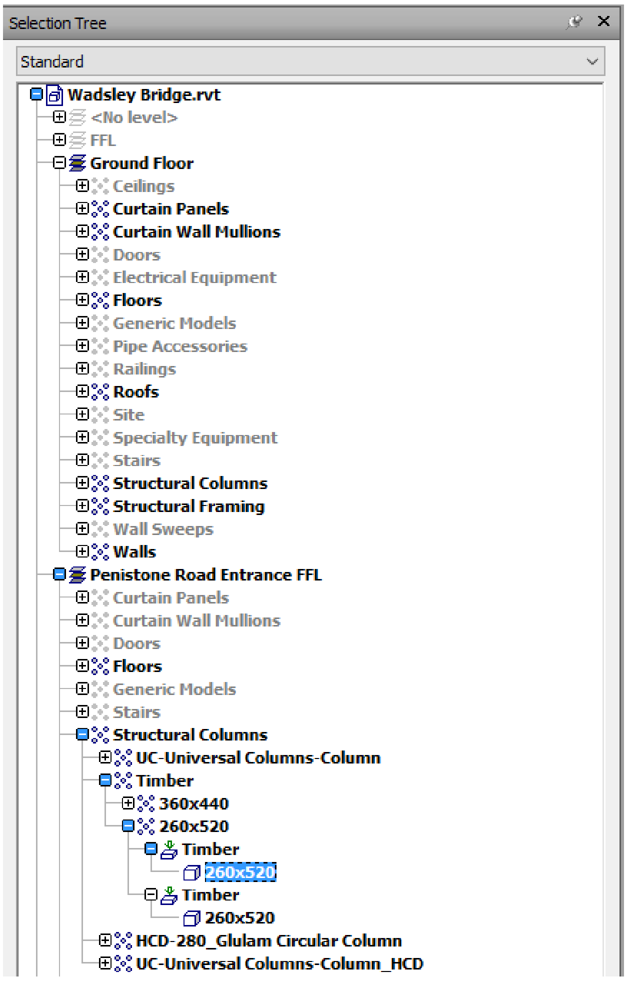
[4] Revit uses layers to structure building models. The user can define these layers in any way they choose. Examples might be layers for each floor of the building or separate layers for the structure, envelope and fit-out. In the Revit files supplied for these case studies the layers were not consistently defined between models but generally included a separate layer for ground floor, mezzanine (where present) and roof level.

[5] Revit families are groups of building elements with common properties. Examples include structural columns or internal doors (Autodesk, 2017)(Autodesk, 2017)



Selection Tree

Standard

- Wadsley Bridge.rvt
  - <No level>
  - FFL
  - Ground Floor
    - Ceilings
    - Curtain Panels
    - Curtain Wall Mullions
    - Doors
    - Electrical Equipment
    - Floors
    - Generic Models
    - Pipe Accessories
    - Railings
    - Roofs
    - Site
    - Specialty Equipment
    - Stairs
    - Structural Columns
    - Structural Framing
    - Wall Sweeps
    - Walls
  - Penistone Road Entrance FFL
    - Curtain Panels
    - Curtain Wall Mullions
    - Doors
    - Floors
    - Generic Models
    - Stairs
    - Structural Columns
      - UC-Universal Columns-Column
      - Timber
        - 360x440
        - 260x520
          - Timber
            - 260x520
          - Timber
            - 260x520
      - HCD-280_Glulam Circular Column
      - UC-Universal Columns-Column_HCD

Figure 4-4: The Navisworks selection tree with an example of the Revit layers and objects from a Sainsbury’s supermarket model. The selected glulam structural column (highlighted blue) is the same item as is selected in the graphical workspace depicted in Figure 4-3

4.3.3 Checking and Exporting QTO Data

Options in the software allow the user to hide all the objects which have already been added to the QTO or to reveal these and hide all others. In this way, the user can visually check progress and identify which model objects still need to be added to the QTO. Beyond this, there is little functionality to verify or check the data for errors. Navisworks does not have any built-in functionality to interrogate or create reports of the quantity data. Instead, Navisworks allows all the quantities to be exported to a Microsoft Excel file where such further processing and evaluation is more easily undertaken.

The quantities generated using Navisworks were checked for consistency against quantities produced manually for the same building or, if these were not available, for a building with similar specifications. Anomalies identified were rectified either by making changes to the way the model objects were assigned to the different categories in the item catalogue or resource catalogue or by introducing geometric conversion factors into the Excel file. Examples of these corrections are described in section 4.4.3.

4.4 Implementing an Embodied Carbon Calculation Using Navisworks QTO and Microsoft Excel

For the embodied carbon calculation process implemented in this research, an item catalogue was created based on the categories of the RICS NRM (2012b). This provided the basis for the results of the embodied carbon calculation in Excel to be readily reported against the NRM categories. The NRM was chosen because it is based on UK practice and is intended to 'provide a standard set of measurement rules that are understandable by anyone involved in a construction project' (Royal Institute of Chartered Surveyors, n.d.). These categories are displayed in Table 4-2, where entries in italics are additions that are not derived from the NRM.

Table 4-2: Categories of building element based on the RICS New Rules of Measurement

Categories	Sub-Categories
Substructure	
Superstructure	
	Frame
	Upper floors
	Roof
	Stairs and ramps
	External walls
	Windows and external doors
	Internal walls and partitions
	Internal doors
Internal Finishes	
	Wall finishes
	Floor finishes
	Ceiling finishes
Fittings, furnishings and equipment	
	Architectural fit-out
	Retail fit-out
Services	
	Sanitary installations
	Services equipment

4.4.1 Linking Quantity Data to Carbon Factors

One of the key challenges of implementing an embodied carbon calculation using BIM data is how to link carbon data to the quantities from the BIM model. Whilst the focus of this research is on embodied carbon, the same problem applies to other environmental impact data associated with full LCA. Díaz and Antön (2014) have described the main requirements for integration of LCA and BIM as being avoidance of data re-entry; real-time appraisal; whole building assessment; and an easy-to-use interface. There is currently no mechanism in standard BIM software reviewed for this research or in publically accessible databases of carbon factors for establishing or automating a link between the two. This is a key barrier to preventing the need for data re-entry (Schwartz et al., 2016).

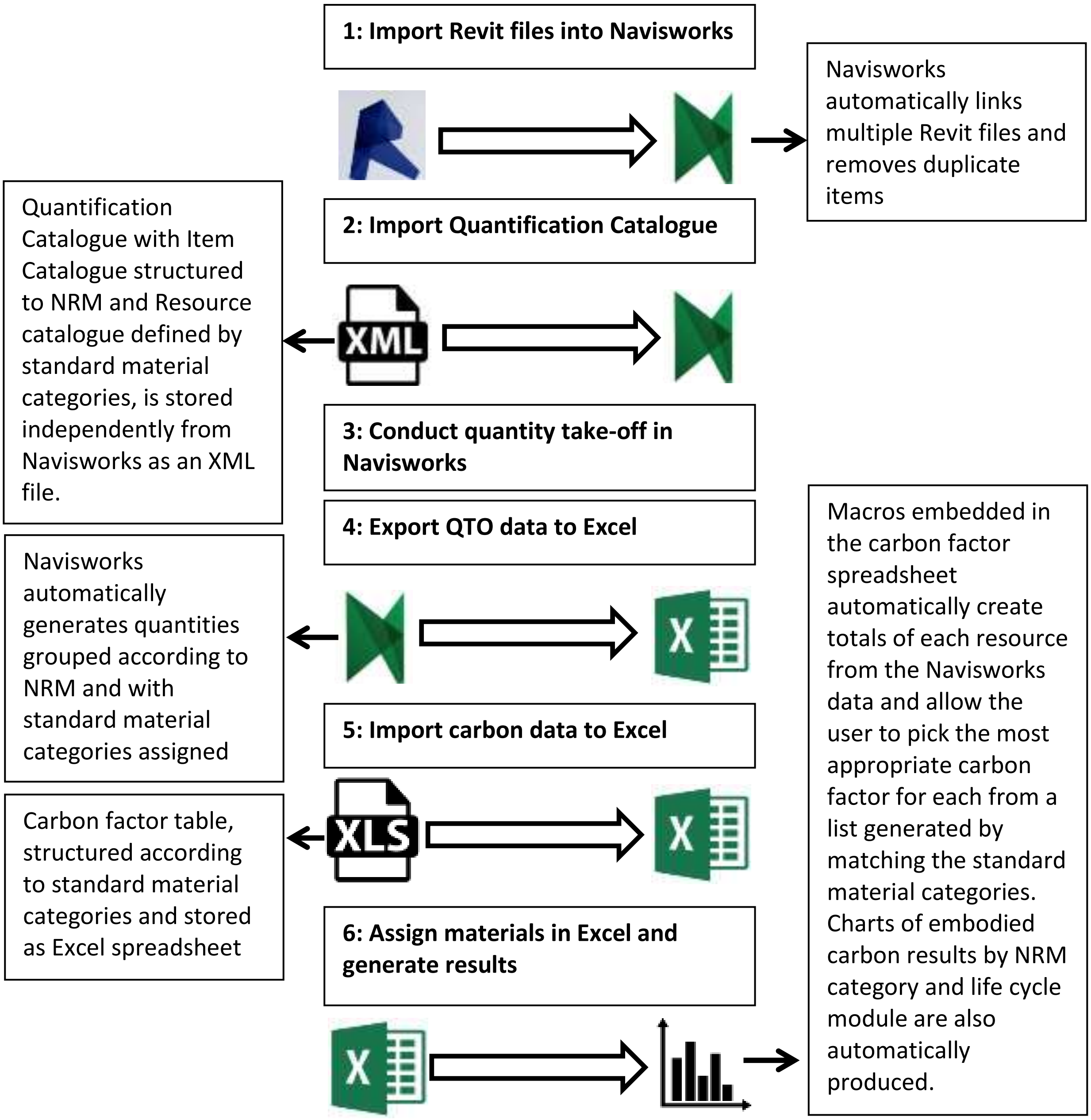
Based on the review in section 3.3.3, of the previous chapter, the two commercial packages which perform LCA within a BIM software environment are Tally and Impact. These both use a similar approach to overcoming this problem, which is to have an integrated set of LCA data that is structured according to different building elements. The user must still choose the appropriate material or materials to assign to each part of the model, but rather than reviewing the entire LCA dataset to find the right match, the software presents a reduced set of relevant options. Similar approaches have been proposed in academic research on this subject (Kulahcioglu, Dang, & Toklu, 2012).

Another area of academic work has focussed on the application of semantic web principles to LCA data (Zhang et al., 2015; Bertin et al., 2012). Semantic web is a concept where data are stored in such a way that they can be read and understood by a computer, in order to allow increased automation of data processing tasks such as linking to other data (Cambridge Semantics, 2014). Semantic web appears to offer promising advances in automating BIM-based LCA tasks, however it is an emerging technology (Schwartz et al., 2016) and its implementation requires knowledge of appropriate programming languages such as Web Ontology Language (OWL) or Semantic Web Rule Language (SWRL) (Zhang et al., 2015) which puts it beyond the scope of this work.

Finally, Jrade and Abdulla (2012) have proposed a method of incorporating existing material identifiers, used in a particular LCA tool, into the meta-data for BIM objects. In this way, the BIM data can be exported with these identifiers and this provides the mechanism for subsequently importing the quantity data into the LCA tool.

The method adopted here draws on the principles of each of the three approaches described above. A common set of material categories was defined which were used to codify both the quantity data and the carbon factor data. This is analogous to semantic web principles, albeit in a very simplified implementation, since it provides the two datasets with a machine readable parameter with common meaning. The creation of a carbon factor data set in a dedicated format is akin to the approach adopted in Tally and Impact. However, here the data are in an open and editable format, allowing the user to update the data set with new carbon factors when these become available or to amend the carbon factors to make them more appropriate for a particular project. Finally, the use of a common identifier to facilitate the link between the two sets of data is closely related to Jrade and Abdulla's (2012) method. Yet where their approach restricts the user to a particular LCA tool, the method used here is independent of the source of embodied carbon data.

Figure 4-5 shows the structure of the embodied carbon calculation process developed for this research and the practical implementation of the different elements of the process is explained below.



Navisworks automatically links multiple Revit files and removes duplicate items

Quantification Catalogue with Item Catalogue structured to NRM and Resource catalogue defined by standard material categories, is stored independently from Navisworks as an XML file.

Navisworks automatically generates quantities grouped according to NRM and with standard material categories assigned

Carbon factor table, structured according to standard material categories and stored as Excel spreadsheet

Macros embedded in the carbon factor spreadsheet automatically create totals of each resource from the Navisworks data and allow the user to pick the most appropriate carbon factor for each from a list generated by matching the standard material categories. Charts of embodied carbon results by NRM category and life cycle module are also automatically produced.

Figure 4-5: Process for conducting an embodied carbon calculation using BIM data

Notes:
NRM = New Rules of Measurement
XML = Extensible mark-up language – a file type which defines how data should be read

= Autodesk Revit; = Autodesk Navisworks; = Micrsoft Excel; XML = XML file XLS = Excel file

Image Sources: Autodesk, Microsoft and Symbolsnet.com

Since the Navisworks quantity data are exported in Excel format, the carbon data was also compiled in Microsoft Excel. The first iteration of this carbon data was based on the Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011) since at the time this aspect of the research was undertaken, this was the most comprehensive (in terms of construction materials covered) source of publically available, UK specific embodied carbon factors that was identified. The data were therefore structured into material categories based on the groupings from the ICE data. These material categories were maintained, with some minor alterations, as additional carbon factor data were added to the dataset. The material categories used for this research are shown in Table 4-3. They are not intended to be a definitive list but are presented here as an example of how such an approach can facilitate the linking of these two datasets in practice.

Table 4-3: Material categories assigned to both carbon factor and material quantity data to allow the linking of the two datasets to be semi-automated (adapted from Hammond & Jones, 2011)

Material Categories
Aggregate
Asphalt
Bitumen
Blockwork
Brick
Carpet
Cement
Ceramics
Clay
Concrete
Doors
Glass
Insulation
Lime
Linoleum
Metals
Miscellaneous
Mortar
Paint
Paper
Plaster
Plastics
Renewables
Rubber
Sealant/Adhesive
Steel
Stone
Terrazzo
Timber

The resource catalogue feature of Navisworks was used as the mechanism for assigning these same material category names to each of the elements of the BIM model. Each resource in the catalogue must be given a name. The names given were all preceded by the relevant material category. In the exported Excel quantity file, these names could then be cross referenced against the categories in the table of carbon factors.

4.4.2 Carbon Factors

Six different potential sources of carbon data were identified in the literature review and these were ranked in terms of their data quality, based on the judgements of 10 experts. Full details of the methods and results of this data quality ranking exercise are given in Chapter 5. The ranking, which is shown in Table 4-4, provided a basis for prioritising the selection where multiple carbon factors were available for the same material.

Table 4-4: Six potential sources of carbon factor data ranked according to their data quality, evaluated by expert judgement as part of this research (see section 6.1)

Rank	Source
1	EPD (EN 15804 compliant[1])
2	Factor from commercial LCA database
3	PAS 2050[2] compliant carbon footprint
4	Industry data
5	Government data
6	Factor derived/aggregated from literature

EPD = Environmental Product Declaration
PAS = Publically Available Specification
1 British Standards Institution (2014a)
2 British Standards Institution

4.4.2.1 Cradle to Gate Emissions – Modules A1-3

As has been mentioned above, the Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011) was used to establish an initial set of carbon factors for use in the assessments. The ICE only provides data for the cradle to gate life cycle stages. The data were compiled prior to the publication of EN 15804 and so do not refer to the life cycle module in that standard. The scope of the ICE data is broadly comparable to modules A1-3 (British Standards Institution, 2014a). However, the carbon factors in the ICE are derived from literature. The data quality assessment ranked this type of carbon data as having the lowest data quality of the six types of data source assessed. Therefore, wherever possible, the carbon factors in the ICE database were replaced with alternative values from one of the other five sources. Wherever appropriate, data from EPD were used, and often these include additional life cycle stages beyond A1-3. However, few EPDs include all stages and several EPDs were used in this research that only include the cradle to gate stages. Additional data were therefore required to estimate the carbon emissions from the subsequent life cycle stages. In general, the availability of data for these later stages of the life cycle was found to be poorer than for the cradle to gate stage. Previous studies have excluded some or all of these stages due to the lack of data (Aye et al., 2012; Citherlet & Defaux, 2007).

The following sections describe the derivation or estimation of emissions factors for the life cycle stages beyond the cradle to gate which were applied when specific data were not available. These were included in the spreadsheet of carbon factors as default values that can be easily amended if specific data are available or become available at later stages in the design and construction process.

The evidence from those studies that have included these later stages of the life cycle is that their impact is usually relatively small compared to the cradle to gate stage. Estimates suggest that transport emissions and the end of life stage may contribute as little as 1-2% each to the total cradle to grave embodied carbon of the building (Darby, 2014; Monahan & Powell, 2011; Kofoworola & Gheewala, 2008, 2009; Adalberth, 1997). Using such estimated data in the early stages of the design is therefore not expected to lead to significant errors in the final results. Moreover, since the carbon factors in the tool can be edited and updated at any time, the accuracy of the results for these life cycle stages can be improved as data availability improves.

4.4.2.2 Transport to Site – Module A4

For the transport to the construction site, emissions were based on average data for UK freight as shown in Table 4-5 and distances were based on average UK road freight statistics for the relevant category of material as shown in Table 4-6. Where a product was expected to be imported from overseas, an estimate of the typical transport distances involved was made on a case by case basis and the details of these are provided in the relevant building case studies in section 4.5.

Table 4-5: Average carbon emissions for different modes of transport used in the embodied carbon assessments for this research. Based on UK Government statistics (Department for Environment, Food and Rural Affairs, 2015)

	Road	Rail	Sea
Carbon Emissions (kgCO2e/kg.km)	1.14×10^{-04}	2.60×10^{-05}	1.32×10^{-05}

Road freight emissions based on average for all classes of HGV and with average loads
Sea freight emissions based on data for an average cargo ship

Table 4-6: Average road transport distances assumed for the purpose of estimating emissions for the transport of construction materials from the production location to construction site (Module A4 in EN 15804 (British Standards Institution, 2014a)).

Material Category	Road Transport Distance (km)[1]
Aggregate	100
Asphalt	87
Bitumen	87
Blockwork	136.4
Brick	136.4
Carpet	289.6
Cement	136.4
Ceramics	136.4
Clay	96
Concrete	24[2]
Door	185
Glass	136.4
Insulation	185
Lime	96
Linoleum	185
Metals	255.2
Miscellaneous	185
Mortar	136.4
Paint	185
Paper	271
Plaster	136.4
Plastics	185
Renewables	185
Rubber	185
Sealant_Adhesive	185
Steel	255.2
Stone	96
Terrazzo	136.4
Timber	271

All distances are for delivery and return journey

[1] All data from Department for Transport (2016) except concrete

[2] Concrete average distance based on Mineral Product Association (2013) data for ready mixed concrete

Both the distance and the vehicle emissions factor can be overridden in the Excel calculation if more specific data is available.

4.4.2.3 Construction – Module A5

At one stage, Sainsbury's monitored and recorded the energy used on sites which it was hoped could provide a useful basis for establishing typical emissions for construction activities. However, the energy monitoring function was discontinued part way through this research. Samples of the data recorded for a number of construction site were obtained but were found to be inadequate. This was because no records were kept of fuel use for vehicles and generators and so data only covered electricity and water consumption. Additionally, for these utilities, readings were found to be irregular with frequent gaps and anomalies.

In order to provide a default value for this life cycle stage when specific data for a given material were not available, a factor of 10% of the cradle to gate emissions was applied. This was determined based on the evidence of the prior work conducted for Sainsbury's (dCarbon8, 2007, 2008, 2009, 2010) and further support in the literature. Kofoworola and Gheewala (2008, 2009) found construction emissions to be around 10% in their assessment of commercial construction, albeit based on data from Thailand. Darby's (2014) study of a warehouse building in the UK of similar proportions to the supermarket buildings assessed here found that construction emissions were around 6.5% of the cradle to gate emissions.

4.4.2.4 Maintenance, Repair and Refurbishment – Modules B1-5

Through discussions with Sainsbury's staff and observations of refurbishment projects that were undertaken whilst this research was ongoing, it was established that supermarkets are typically refurbished on a 10 yearly cycle. The scope of these refurbishments varies from site to site and is determined on the basis of a site survey. On the basis of these observations, a typical refurbishment scope was deemed to be the replacement of the retail shelving and cabinets and mechanical services. Any other repair and maintenance activities were not included in the assessments unless specific data were available for a given component from an EPD. The evidence from previous studies suggests that the impact of these activities is negligible when assessing a whole building (Kofoworola & Gheewala, 2009)

4.4.2.5 End of Life Demolition and Disposal – Modules C1-4

Data for this stage of the life cycle were found to be more widely available than for the stages described above. Of the 283 material carbon factors listed in the spreadsheet, 124 or 43% have specific values for end of life embodied carbon compared with just 4% which have a value for transport (A4) and 1% for construction (A5). For those materials that do not have a specific factor for this stage of the life cycle, emissions were assumed to be 2% of the combined cradle to site and construction (A1-5) emissions. As with factor applied for construction emissions (see 4.4.2.3 above), this was based on data from Sainsbury's previous studies (dCarbon8, 2007, 2008, 2009, 2010) and evidence from the literature (e.g. Darby, 2014).

The full table of carbon factors included in the calculation spreadsheet is reproduced in Appendix C:

4.4.3 Limitations of BIM for Generating Quantities for an Embodied Carbon Assessment

One of the objectives of the research is to demonstrate the suitability and limitations of Sainsbury's BIM models to facilitate the automatic generation of material quantities data for an embodied carbon assessment. In order to achieve this objective the BIM QTO procedure outlined above was applied to conduct embodied carbon assessments of three case study buildings. In conducting these case study assessments and validating the accuracy and consistency of the quantities, it was possible to identify a number of limitations in the models. By comparing these across the three models, five different distinct types of limitation were identified and these were:

- Simplified geometry
- Composite components not fully modelled
- Materials not specified to the required level of detail
- Quantities or dimensions not available
- Objects not clearly or not consistently named
- Duplicated objects (both within a single file and due to incorrect alignment of multi-file models)

4.4.3.1 Simplified Geometry

One error identified in all four models tested was that some objects with hollow or profiled cross sections were modelled as solid volumes. Examples where this occurs are roof fascias and flashings and window glazing and frames, including mullions and transoms in curtain wall systems. Fascias are commonly used to conceal and protect the edges of the main roofing construction and the joints with walls. Similarly flashing is used to protect joints between different elements and prevent ingress of water. All examples of these in the four models were made from profiled aluminium. Mullions and transoms are vertical and horizontal dividers between panes of glass in a window or glazed curtain wall system. These mullions and transoms, like the frames, were aluminium in all four models and would be expected to have a profiled cross section similar to that shown in Figure 4-7 below.

The quantities generated by Navisworks for these items were found to be based on a solid cross section. Such simplifications are, apparently, adequate for the purpose of design, construction and costing. However, when used to generate quantities for the purpose of embodied carbon assessment, they lead to significant errors. Figure 4-6 shows the cross section of a curtain wall transom from one of Sainsbury's BIM models, as represented in Navisworks 3D viewer. The adjacent Figure 4-7 shows an example cross section of a transom taken from a manufacturer's product literature.

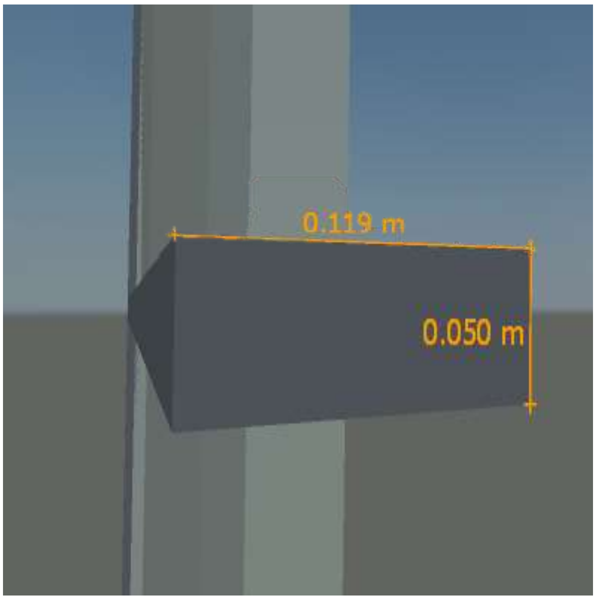


Figure 4-6: Cross section of a curtain wall transom modelled as a solid in the BIM

Figure 4-7: Detailed cross section of a sample curtain wall transom (Tradewind Distribution, n.d.)

Based on the quantities extracted from the BIM model, each linear meter of mullion or transom contains 0.00595 m^3 of aluminium. Based on manufacturer's data, the true volume was estimated to be 0.00115 m^3 per linear meter (European Aluminium Association, 2016). This value was used as a proxy for calculating the actual volume of aluminium in the window frames, mullions and transoms. Table 4-7 below shows the impact that this revised volume has on the estimated mass of aluminium for each of the supermarket buildings assessed.

Table 4-7: The volume of aluminium for curtain wall framing (including transoms and mullions) as estimated directly from the BIM model and by proxy data

		Total volume of aluminium for window and curtain wall framing (m^3)		
	Cross sectional area (m^2)	**60k Model Store**	**Thanet**	**Leicester North**
BIM Value	0.00595	6.40	12.41	1.68
Proxy Value	0.00115	1.24	2.40	0.32

The volumes taken straight from the BIM model are almost a factor of 6 higher than the estimated volume using the proxy data.

Further simplifications in the BIM model can be identified by comparing Figure 4-6 and Figure 4-7. The fittings which hold the glazing into the frame, including the seals, spacers and screws are not modelled in the BIM. The impact of these was deemed to be below the cut-off criteria applied and are therefore not included in the embodied carbon assessment. More significantly, the glazing is also modelled as a single volume rather than as two 6mm panes with an air (or inert gas) gap. Therefore a proxy for the true glazing volume was derived by multiplying the area of glazing by 0.012 m.

4.4.3.2 *Composite Elements Modelled as Homogeneous Objects*

A further modelling simplification identified during the quantity take-off process was the amalgamation of composite elements into homogenous objects. The most frequently encountered example of this was the internal partition walls. In reality these are constructed from a lightweight metal framing system with two layers of plasterboard attached to each side. Illustrations of such a system are shown in Figure 4-8.

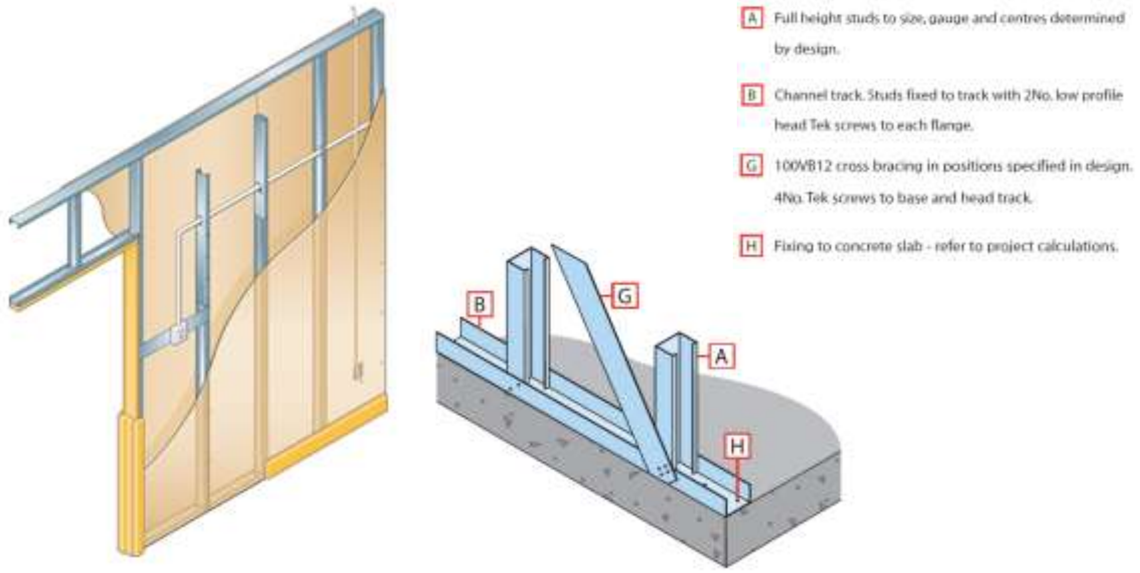


Figure 4-8: Cut-away illustrations of a metal framing system for internal partition walls (Metsec)

These partition walls in all three BIM models assessed were not fully detailed to reflect this construction. Instead they were modelled as a single homogeneous object. Thus, when quantities were extracted, the area and volume quantities represented the combined volume of the steel framing, the voids, and the plasterboard. Moreover, where these walls had a tiled finish, the tiling was also not separately modelled but was included in the object's total volume.

In order to generate quantities of each of the individual elements of these walls, proxy values were estimated for the quantity per square meter (plasterboard and tiles) or per cubic meter (steel framing). For plasterboard and tiles, the quantities could be simply estimated multiplying their thickness by the wall area. For the steel frame, manufacturer's installation guides were used to establish the profile and spacing of the vertical and horizontal members. The frame for a basic wall with no openings consists of a channel at the top and bottom with a u-shaped profile and vertical studs spaced at 600mm which have a c-shaped profile. The profiles can be seen in Figure 4-8 above where object A is a c-shaped stud and object B is a u-shaped channel. Due to the vertical orientation of the studs, the quantity of steel per cubic meter of wall is slightly higher for a long low wall than for a narrow but high wall. A number of wall configurations, including single and double door openings, which require additional steel framing, were modelled to establish an average volume of steel per cubic meter. The walls in the model were assigned to the relevant category in the Naviworks item catalogue in order to generate a measure of the total surface area and volume. The resource catalogue function of Navisworks was used to assign the correct quantity of light gauge steel, plasterboard and, where applicable, tiles to these walls.

Further examples of composite elements that were similarly lacking in detail included the composite steel deck roofing, timber cassette roofs and the steel sandwich panel wall cladding.

4.4.3.3 Materials Not Specified to the Required Level of Detail

A lack of detail for material specifications was the most commonly encountered limitation of all three models. In terms of the contribution to the total embodied carbon, concrete in the sub-structure was the main example. In all the models, there was no indication of the strength class of concrete elements, nor any details of whether and what proportion of steel reinforcement was included. The insulation in the building envelope was, in some cases, only listed as mineral wool without specifying the type (stone or glass wool) or the density. Similarly, much of the timber included in the models did not have any details included as to the type or density, both of which can have an important effect on the embodied carbon factor (Rüter & Diederichs, 2012)

At early design stages, it is likely that some of these details are yet to be decided. Moreover, discussions with Sainsbury's design consultants about this issue revealed that in some cases the detailed specifications are determined by the main contractor. However, the inclusion of indicative material specifications in the model, perhaps based on previous buildings, would make it easier for the user conducting an embodied carbon assessment. Without any details in the model, further work is required to establish what a typical specification for a given building element might be. For supermarkets the level of repetition or similarity between each building is expected to be relatively high compared to some other types of commercial buildings such as offices. It should therefore be possible to establish typical details for the main elements of the substructure, frame and envelope.

For this research, two of the buildings assessed in the case studies had already been built. It was therefore possible to establish the actual specifications of most of the materials where this detail was not included in the BIM model. For the 60k Model, which is a design template rather than a real building, the details were taken from the manually produced bill of quantities which is used by Sainsbury's to establish the build cost of the model. These details could be included into the BIM models as typical specifications for the purposes of conducting early design stage embodied carbon assessments. If this were done would need to be made clear in any contractual documentation that these details are not to be construed as design information and do not imply that Sainsbury's is accepting design responsibility.

4.4.3.4 Quantities or Dimensions Not Available

For some objects in the model, the QTO did not generate any quantities, or only a limited number of dimensions were available. For example, the roof lights in all the models only generated a count of the total number of instances but no details of dimensions or volume. Similarly, the shelving and some of the other objects for the fit out only generated a quantity for the total length in linear meters. This was despite the fact that these items appeared in the graphical workspace with full geometry. The reason for this is that the take-off process in Navisworks relies on meta-data. Meta-data is one of the distinguishing features of BIM that separates it from traditional computer aided design. If an object does not have geometric meta-data or if some of that data is missing then Navisworks is not able to generate quantities properly (Smith, 2013). For these examples, it was necessary to determine what, if any quantity data could be extracted and compare this with the best available carbon factor data to establish what additional information was needed.

Where the denominator of the carbon factor functional unit matches the units of the material in the QTO, the two can simply be multiplied together without any further steps. For example, if the carbon factor is quoted in $kgCO_2e/m^3$ and the material quantity is available in cubic meters, multiplying the two values together gives the desired result of $kgCO_2e$. Where the units do not match, a conversion must be carried out. None of the objects in the Sainsbury's models included any quantity data for material mass, although this can be included in BIM meta-data. For objects in the model with full geometric meta-data, the quantities were available in either length, area or volume. Where carbon factors were given per unit of mass, the density of the material is all that is required as a conversion factor. Table 4-8 provides a matrix of all the quantity units encountered in the QTO data for Sainsbury's BIM models and all the carbon factor units encountered in EPD and shows the data required as a conversion factor for a given combination of quantity.

Table 4-8: Matrix of conversions used to ensure consistency of units between material quantities and carbon factors for each of the different combinations of unit encountered

	Carbon factor unit (kgCO2e per …)		
Material Quantity Unit	**mass**	**volume**	**area**
mass	1	1/density	1/(density x depth)
volume	density	1	1/depth
area	depth x density	depth	1
length	Area x density	area	depth
count	Volume x density	volume	area

The presence in the Sainsbury's BIM models of objects for which geometry was not available after applying the QTO procedure indicates that these objects are not fully BIM compliant. These instances are therefore not examples of limitations of BIM but limitations of non-BIM design and serve to illustrate the difference that fully implemented BIM makes to the QTO process.

Nevertheless, these objects are present in what are considered to be examples of BIM-designed supermarkets. The lack of geometric meta-data for these objects may not be a hindrance for other applications of BIM. However, for conducting embodied carbon assessments, full geometric meta-data are required in order to generate appropriate quantities of materials. Sainsbury's should therefore prioritise implementing full BIM compliant modelling for all the parts of their models if they wish to make full use of BIM for conducting embodied carbon assessments.

4.4.3.5 Objects Not Clearly or Not Consistently Named

When conducting the QTO in Navisworks, the user must establish what an object in the model is before it can be correctly assigned. There are a number of ways to do this, but the two most obvious indicators are the graphical representation of the object and the object's name. In the graphical workspace (see Figure 4-3 above), it is generally straightforward to distinguish whether an object is a structural column or part of an external wall. The name listed in the selection tree (see Figure 4-4 above) provides a further indication, for example helping to distinguish a timber structural column from a steel one. Should further information be required, the objects properties can be viewed by opening the properties window. Here any details of the material that have been specified can be reviewed. However, this additional step slows down the QTO process. Providing names for objects that allow easy and intuitive identification would help to make the QTO procedure more efficient. Maintaining consistency with the way that different but related items are named can also help improve the workflow. Firstly, it allows the user to more readily recognise a related set of objects in the selection tree. Secondly, it would facilitate more efficient searching for objects. Navisworks has a powerful search tool which allows objects to be selected based on multiple criteria. If, for example, all glulam objects have the term glulam in their name, then the search function could be used to select all objects with this term which are also part of the structural column object category. In this way, all the glulam structural columns could be identified with a single search. In the example shown in Figure 4-4, the term glulam has been included in the name of one set of objects, but another has been labelled as timber. This inconsistency limits the scope to use searches to identify related objects and assign them to the relevant quantification category with one action.

4.4.3.6 Model Errors

A number of apparent modelling errors were identified and it is likely that there are many possible kinds of errors beyond those encountered in the course of this research. Examples of errors identified included duplicated objects, objects located on incorrect layers in the model and incorrect alignment of multi-file models. The misalignment is only apparent when two Revit files are linked together in Navisworks. The modelling space in Revit has a coordinate system linked to an origin and when a building is designed, its location and orientation relative to the coordinate origin is specified. It is this feature which Navisworks uses to merge two separate Revit files together so that the designs are superimposed on one another. If the location and orientation do not match then the models will not align properly in Navisworks. The main problem that this introduces occurs if the same elements are found in both files. This is commonly the case for major components such as the structure which may be included in multiple files in addition to the structural engineers file for the purposes of setting out other aspects of the design. If the files are properly aligned, Navisworks can identify these items and ensure that duplicates are removed but this does not happen when the files are misaligned.

The limitations that these and other errors introduce are not exclusive to the task of embodied carbon assessments since errors may have negative impacts on other functions of BIM. No specific recommendations or approaches to addressing errors were therefore considered or implemented in this research. As a general recommendation, model checking, quality assurance procedures and the mitigation of errors should be an integral part of the BIM design process regardless of the desired applications.

4.4.4 Life Cycle Assumptions

When embodied carbon emissions are assessed from cradle to grave, an assumption must be made about the service life of the building. Although annual operational emissions were not included in the assessments presented here, embodied carbon impacts can arise during the use phase due to maintenance and refurbishment activities. Here, only the refurbishment is considered because data were not available to assess the embodied carbon arising from maintenance activities.

Amongst LCA based studies of buildings that were reviewed for this research, there is significant variation in the assumptions made about building service life. Assumptions range from 30 to 100 years for whole buildings (Ramesh, Prakash, & Shukla, 2010; Sartori & Hestnes, 2007) and 10 to 100 years for buildings products (Cabeza et al., 2014).

The assumptions about service life of construction products are typically justified on the basis of their technical durability. However, this approach implies that technical factors are the main determinant of replacement frequency. This is not consistent with evidence presented by O'Connor (2004) which suggests that other non-technical aspects such as commercial considerations and aesthetics play an important role. In reviewing typical practices in retail, it was found that supermarkets tend to conduct refurbishments on a predetermined cycle of around 10 years (Deloitte, 2010).

Similarly, it is common for building embodied carbon assessments to assume a building service life of 50 years. In some cases, this is predicated on design codes such as the Eurocodes, which quote 50 years as the indicative design life of 'building structures' (British Standards Institution, 2002, p. 28). It has been shown however, that such statements of nominal design life have little bearing or connection to the actual durability of buildings (Aktas & Bilec, 2012; O'Connor, 2004). Furthermore, assessing embodied carbon using such assumptions takes no account of the non-technical issues that can affect building service life such as changing land values and occupant needs which often have a greater influence on actual service life than durability.

In the specific case of supermarket buildings, only one study was found that assessed the whole lifecycle using an assumed service life of 20 years, stating that such buildings typically have a short life expectancy (Densley Tingley, 2013). Of the unpublished embodied carbon studies of supermarkets conducted on behalf of Sainsbury's, four assumed a service life of 30 years (Deloitte, 2010; dCarbon8, 2007, 2008, 2009) whilst one, which covered two different buildings, assumed a 60 year service life for both (dCarbon8, 2010). In all the studies, no justification was given for the service life length used.

Richardson et al. (2014) conducted a review of the actual ages of a range of existing and demolished supermarkets in the UK. Data on the ages of almost 600 existing (still trading) supermarkets was gathered as well as additional data on supermarket closures. Data on store closures was provided by Sainsbury's directly and for other UK supermarket chains was sourced from local records such as online news reports. Fifteen closures were identified, dating back to 2007. Of these, eight are known to have been demolished, whilst the remaining seven are excluded because their current status could not be verified. The ages of the existing stores are presented in Table 4-9 and those of the 8 demolished stores are shown in Table 4-10 below.

Table 4-9: Age distribution of a selection of existing (operational) UK Supermarkets (Richardson et al., 2014, p. 6 Table 1)

Age Range	**0-15 Years**	**15-25 Years**	**25-35 Years**	**35-45 Years**	**45-55 Years**
Percentage of existing stores	40%	32%	19%	7%	2%

Table 4-10: Ages of eight UK supermarkets demolished between 2007 and 2014 (Richardson et al., 2014, p. 6 Table 2)

Store number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	Mean Age
Age at demolition (years)	35	22	15	16	23	26	29	18	**23**

The data for the store demolitions shows that the service life of these stores varied from 15 to 35 years with the mean age being 23 years. The mean age of existing stores is 18 years, and if those less than 15 years old (the earliest date of demolition recorded) are excluded, the mean value rises to 26 years. Therefore, for the assessments presented here, a service life for the whole building of 25 years has been assumed and it has been assumed that all items categorised in the model as *Internal finishes, Services* or *Fittings, furnishings and equipment* are replaced every 10 years.

4.5 Building Case Study Results

4.5.1 Goal, Scope and Boundaries

The primary goal of these case studies was to demonstrate and test the approach to using BIM quantity data for an embodied carbon assessment. Identifying the limitations of the quantity data for this purpose was a key objective of this and these have been detailed in section 4.4.3 above. A further objective within this overall goal was to establish what scope of study could be achieved using the approach developed. The desired scope was the cradle to grave assessment of the whole supermarket including the carpark. However, as the building case studies that follow demonstrate, this has not been possible using the data available from Sainsbury's BIM models. In all three studies, the external areas including the car park were not fully modelled in BIM and so quantities could not be generated. Furthermore, due to a lack of detail in the model, fixings and adhesives and some minor items such as damp-proof membranes were not included in the assessments. Finally, the maintenance and repair of the building and components was not included in the study due to a lack of data for the materials and energy required for these activities. However, the impacts of these activities are expected to be very small relative to the total embodied carbon (Kofoworola & Gheewala, 2009) and their exclusion is therefore not expected to affect the conclusions drawn from the assessment results.

Providing evidence of the embodied carbon impacts of the three case study buildings and how these are distributed between building components and life cycle stages was a further objective of the assessments. The building case studies were selected to allow an assessment and comparison of a number of typical building configurations and construction elements as outlined in section 4.2 above.

The reference study period selected was the same as the building service life, i.e. 25 years. This was established from empirical data for UK supermarkets as explained in section 4.4.4.

In sections 4.5.2 to 4.5.4, the results of the three building case studies are presented and discussed individually and these are followed by a comparison of the outcomes from each in section 4.6.

4.5.2 Case Study 4-1: 60k Model Store

The 60k Model store is a hypothetical store design used by Sainsbury's as a planning tool. It represents the typical standard specification and configuration for a large supermarket from which proposed new schemes are developed. There is also a 30k Model which has half the sales area of the 60k Model and is used when planning smaller supermarkets. Whilst both these standard model stores have the same basic construction and configuration, the 60k Model was used here because at the time the research was carried out, there was no BIM model available for the 30k variant. Table 4-11 provides additional details of the 60k Model.

Table 4-11: Details of Sainsbury's 60k Model Store

Key Facts	
Gross Internal Area	8,746 m^2 (94,141 ft^2)
Sales Area	5,574 m^2 (60,000 ft^2)
Eaves Height:	
Sales	6.5 m
Warehouse	3.3 m
Layout	Single storey, ground level
Frame	Steel portal frame, 12m x 12m grid
Roof	Insulated steel deck
Walls	Composite steel sandwich panels

4.5.2.1 Scope of the assessment

The 60k Model was used by Sainsbury's to develop and test the BIM procedures and therefore the BIM model for this store was the most complete available. It consisted of four linked Revit files for the structure, architecture, mechanical and electrical installation and the retail layout. The case study therefore covers all of these elements. The external works, i.e. the car park, access road and external services such as lighting and drainage were not fully modelled in the BIM files made available and were therefore excluded from the assessment.

4.5.2.2 Material quantities

The quantities for the sub-structure and super-structure extracted from the BIM model are shown in Table 4-12 alongside the calculated mass. Where the model quantities were obtained in cubic meters, the density of the material is used to calculate mass. For non-volumetric quantities, the geometry conversion factors shown in the table were used to convert the quantity into cubic meters. A full table of quantities from the BIM model (including the fit-out items) and selected carbon factors for each material are shown in Appendix D:.

Table 4-12: Material quantities for the substructure and superstructure of the 60k Model extracted from the BIM model.

Items and Resources by Item category	**User's Material Selection**	**Model Quantity**		**Geometry Conversion Factor**	**Mass (tonnes)**	**Wastage (%)**
Substructure						
Boot Beams and Pads						
Concrete - poured reinforced concrete	RC 32/40 (CEM I)	931.35	m³	1	2142.10	4
Floor-slab						
Concrete - poured reinforced concrete	RC 32/40 (CEM I)	1631.07	m³	1	3751.47	4
Superstructure						
Frame						
Steel portal frame						
Steel - Section	Structural section incl fabrication	35.45	m³	1	278.29	10
Steel Purlins						
Steel - Light Gauge Section	Light steel framing	5.53	m³	1	43.41	10
External Walls						
Cladding						
Miscellaneous - Rockspan	Rockspan - 175mm (kg/m²)	2109.94	m²	1	57.26	0
Curtain wall						
Metals - Aluminium Mullions	Aluminium - extruded	1074.93	m	0.00115	2902.31	10
Glass - Glazed curtain walling	Flat Glass - 6mm Pane EPD	1240.42	m²	0.006	1550.53	1
Roof						
Insulated steel deck						
Insulation - PIR	Insulation - Polyurethane	1076.37	m³	1	32.29	15
Plastics - PVC - Roof	Plastics - PVC General	1.98	m³	1	2.63	3
Steel - Sheet - Roof	Steel - Coil (Sheet) - Darby	7.41	m³	1	58.14	22
Canopy Deck						
Steel - Profile Deck	Steel - Decking - IFPS EPD 35mm	731.90	m²	1	5.05	10
Plant Deck						
Steel - Profile Plant Deck	Steel - Decking - IFPS EPD 35mm	638.12	m²	1	4.40	10
Roof Fascias						
Metals - Aluminium Section - Fascias	Aluminium - extruded	0.18	m³	1	0.49	10
Rooflights						
Miscellaneous - Rooflight	Rooflight EPD	72.00	ea	1	1.44	0
Internal walls and partitions						
Blockwork Wall						
Blockwork - 215mm Blockwork	Concrete Block -13 MPa	18.05	m³	1	37.90	20

Items and Resources by Item category	**User's Material Selection**	**Model Quantity**		**Geometry Conversion Factor**	**Mass (tonnes)**	**Wastage (%)**
Mortar - for Blocks	Mortar (1:1:6 Cement:Lime: Sand mix)	1.18	m³	1	1.88	20
Plaster - Plasterboard	Plasterboard	1.05	m³	1	1.00	5
Stud wall						
Plaster - Plasterboard	Plasterboard	163.73	m³	1	155.54	5
Steel - Partition Studs	Light steel framing	3.66	m³	1	28.76	10

- Conversions to mass values shown are based on densities published in CIBSE Guide A **(2006)** and Geometric Conversion Factors shown, where Model Quantities are non-volumetric. For derivation of the Geometric Conversion Factors, see section 4.4.3.
- Wastage rates are based on data from the WRAP Net Waste Tool **(Waste and Resources Action Programme, 2013)**
- Bold text indicates the item categories based on the New Rules of Measurement
- Standard text indicates model objects taken off to the item catalogue.
- Italicised text indicates entries from the resource catalogue assigned to the item
- For details of the User's Material Selections and the associated carbon factors, see Appendix D: and Appendix C:
- CEM I refers to OPC cement

4.5.2.3 Results and Discussion

The results generated by the calculation tool are presented by life cycle stage in Figure 4-9, by NRM category in Figure 4-10.

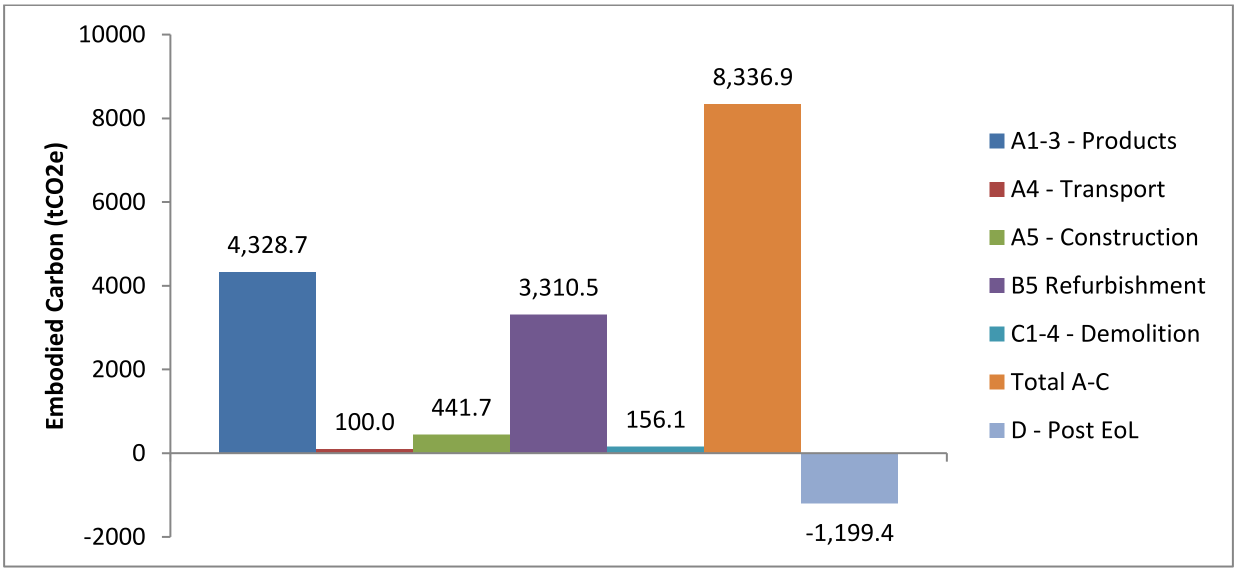


Figure 4-9: Embodied carbon of the Sainsbury's 60k Model Store by life cycle module (according to EN 15978 (British Standards Institution, 2011a))

The total embodied carbon for the 60k Model supermarket was found to be 8,286 tonnes. This is equivalent to just less than 0.95 tCO_2e per square meter of gross internal area. The biggest impact is for the cradle to gate emissions for the products (A1-3), which accounts for just over 50% of the total. The next largest contribution is from the refurbishment (B5). Since almost no data was available for the maintenance or repair of different building components (B1-4), this stage of the life cycle was excluded from the assessment.

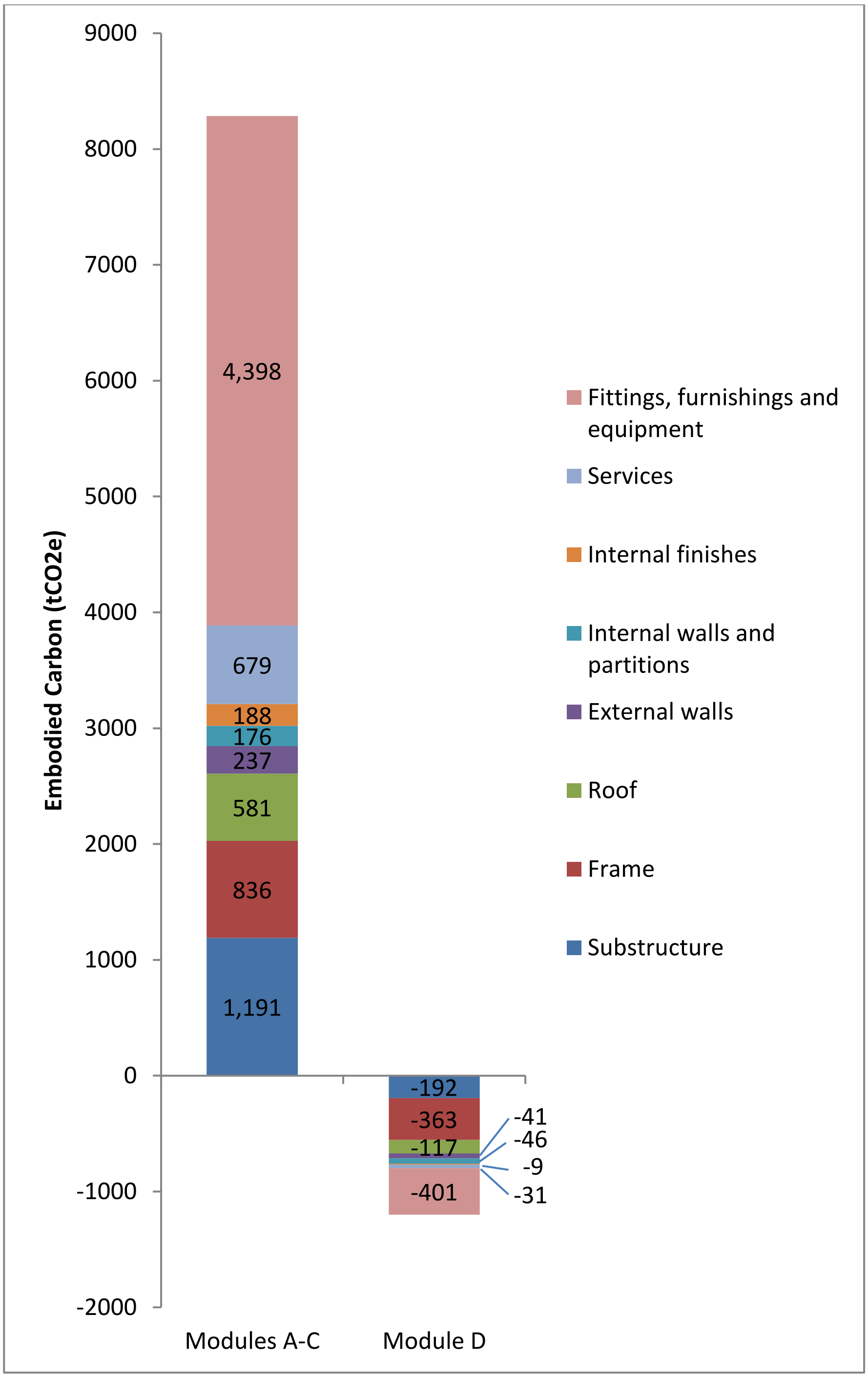


Figure 4-10: Embodied carbon of the Sainsbury's 60k Model Store by building element for cradle to grave (Module A-C) and benefits beyond the end of life (Module D)

From Figure 4-10, it can be seen that the fit out of the supermarket accounts for more than 50% of the total embodied carbon. This is due to the high volumes of steel required for the shelving and the chilled cabinets. This steel is almost exclusively sheet steel, which has a higher carbon factor than the steel sections used in the frame of the building. The frequent replacement cycles that were assumed in the model also contribute to the large contribution of this part of the building. Over a 25 year service life for the building, it was assumed that the fit out is replaced twice, to reflect current supermarket retailers' practice of undertaking major refurbishments approximately every 10 years. This parameter can be easily altered within the model, allowing a simple sensitivity analysis to be carried out to test the effect of different refurbishment frequencies. The effect on the results of changing the replacement frequency to one or three replacements within the life time are shown in Figure 4-11.

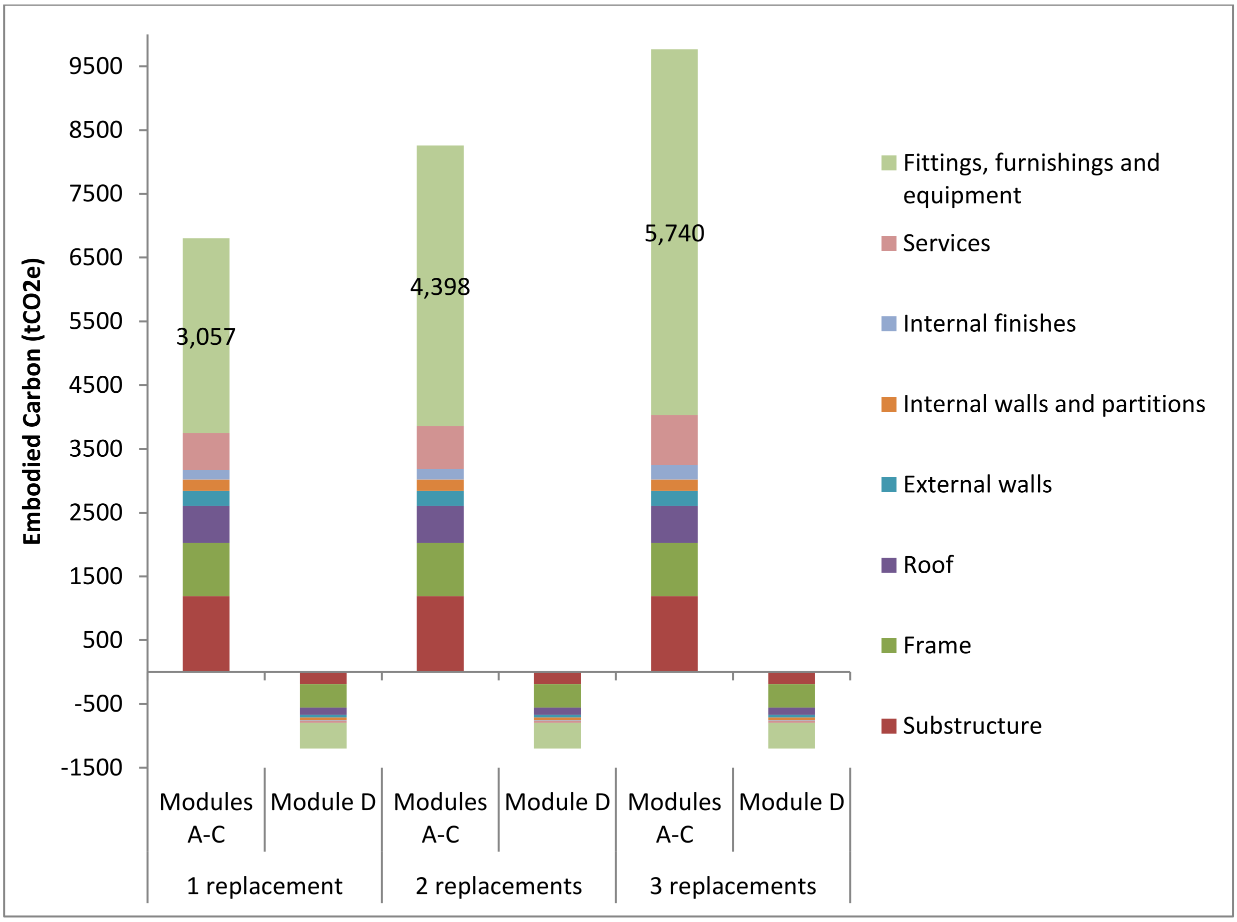


Figure 4-11: Comparison of the effect on embodied carbon of different replacement rates for fit out items

Each replacement of the fit out items contributes just over 1300 tCO_2e to the total embodied carbon and reducing the replacement rate from two in 25 years to just one is equivalent to a saving of just over 16% of the total cradle to gate emissions. This is therefore a key assumption and it is recommended that Sainsbury's undertakes further detailed study of what proportion of the fit out items are replaced in practice and evaluates whether current refurbishment cycles can be extended.

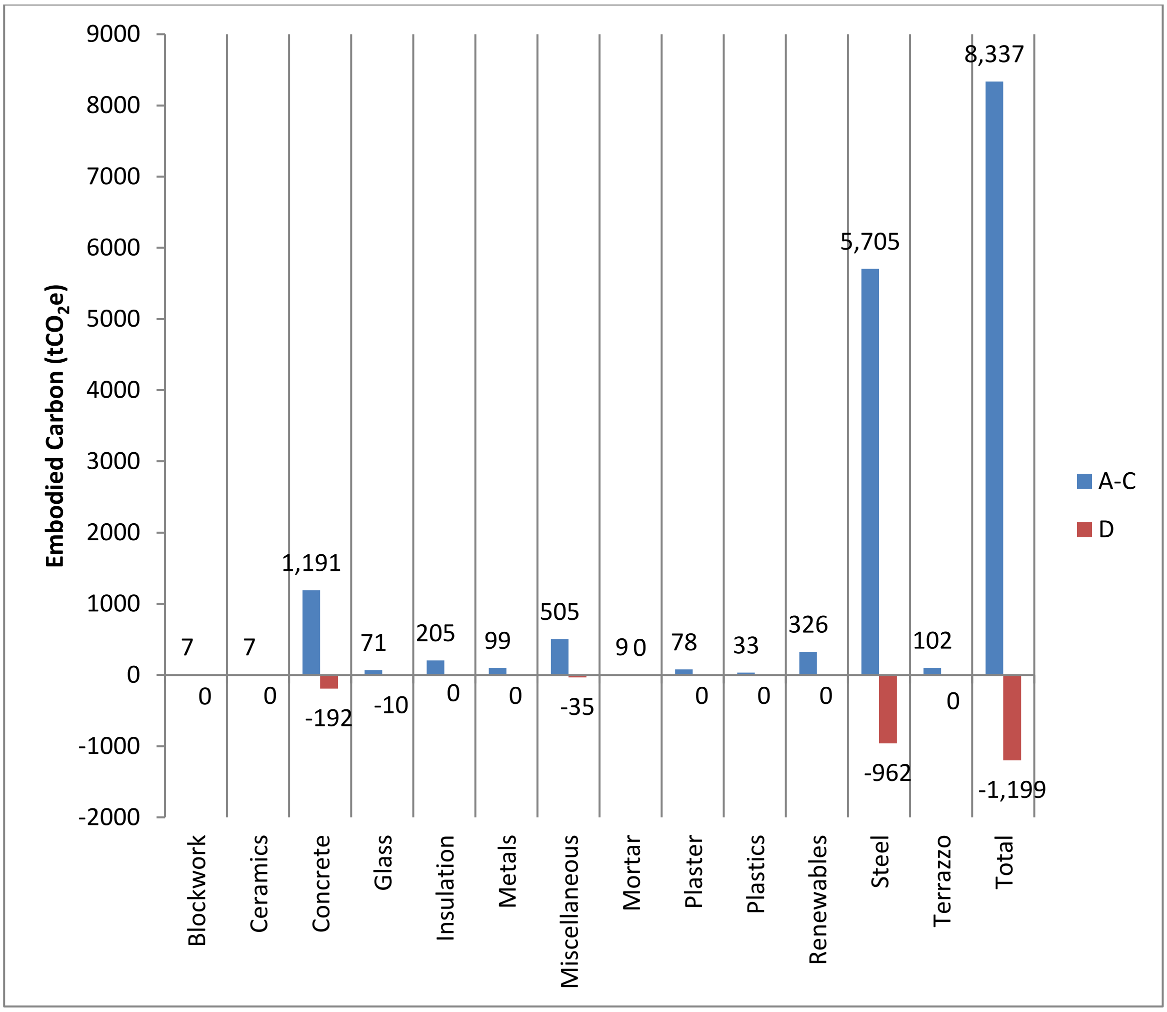


Figure 4-12: Embodied carbon of the Sainsbury's 60k Model Store by material for cradle to grave (Module A-C) and benefits beyond the end of life (Module D)

The results for each material are shown in Figure 4-12 based on 2 refurbishments. Steel and concrete can be seen to make the largest contributions to the total and are responsible for more than 80% of the total figure.

The benefits beyond end of life (module D) include carbon saved through recycling or reuse and from incineration with energy recovery. Based on the data available, the carbon benefit that could be realised if these actions are taken is around 1200 tCO_2e or just under 15% of the total cradle to grave emissions. This lifecycle stage is typically only reported in some EPDs and so the figures estimated here may not represent the full benefits that could be achieved if large proportions of the building materials are sent for recycling, reuse or energy recovery at the end of life. The materials where these benefits are reported and included in the assessment can be seen in Figure 4-12. The recycling of steel contributes around 80% of the total benefits beyond the end of life. However, under the standards for life cycle assessment of buildings, these benefits are defined as being part of a subsequent life cycle and must be reported separately rather than being subtracted from the total (British Standards Institution, 2014a, 2011a). The reason this 1200 tonne carbon saving cannot be credited to the building is that this would lead to double counting since the credit is taken by the subsequent life cycle. In the case of recycling, the recycled material has a lower carbon factor than the virgin material and this difference is what is estimated in module D. If the module D values were incorporated into the cradle to grave figure for the building then the recycled material would need to be given a carbon factor equivalent to the virgin material in order to prevent the benefit being counted twice. The same principle is applied to energy from waste.

However, if these future benefits are not considered at all when the building is designed and built, then there is no incentive for the use of materials that can be recycled or reused. Providing data on these benefits allows designers and decision makers to consider how the use of materials which are recyclable or reusable can reduce the overall climate change impacts of buildings.

4.5.3 Case Study 4-2: Leicester North

Leicester North was selected as a case study because it has a significant amount of timber in the construction. The structural frame in the sales area is engineered glulam timber and the roof is made from pre-fabricated timber cassettes. A number of other supermarkets have also been built in this way, and previous studies for Sainsbury’s have reported notable reductions in embodied carbon through the use of timber (Deloitte, 2010; dCarbon8, 2008). The details of the building are shown in Table 4-13 and comparing these with the details of the 60k Model in Case Study 4-1 shows that the building is 30% larger by gross internal floor area, 10% higher at the eaves in the sales area and 45% higher at the eaves in the warehouse area.

Table 4-13: Details of Sainsbury's Leicester North Supermarket

Key Facts	
Gross Internal Area	11,330 m^2 (122,955 ft^2)
Sales Area	6,638 m^2 (71,453 ft^2)
Eaves Height:	
Sales	7.2 m
Warehouse	4.8 m
Layout	Single storey, ground level
Frame	Hybrid: Glulam for sales area, steel for warehouse and staff areas
Roof	Timber cassettes
Walls	Steel composite sandwich cladding panels

4.5.3.1 Scope of the assessment

The BIM model available covered the structural and architectural designs. Neither of these models provided adequate detail of the external works or the internal fit out to include these in the assessment. Whilst some mechanical and electrical services were modelled, not enough detail was available to fully assess these and so they were also excluded from the study. Therefore, the scope of this assessment was the sub-structure and super-structure and the internal floor finishes.

4.5.3.2 Material quantities

The material quantities generated by the BIM QTO are presented in Table 4-14 alongside the calculated mass and the user material selection, which links the quantity to the relevant carbon data. Full details of the carbon factors for all the materials are given in Appendix E:.

Table 4-14: Material quantities for the substructure and superstructure of Sainsbury's Leicester North, extracted from the BIM model.

Items and Resources by Item category	User's Material Selection	Model Quantity		Geometry Conversion Factor	Mass (tonnes)	Wastage (%)
Substructure						
Floor slab						
Concrete - floor slab	Concrete - RC 32/40 (15% PFA)	2875.00	m³	1	6612.50	4%
Beams and Pads						
Concrete - poured reinforced concrete	Concrete - RC 32/40 (15% PFA)	1353.84	m³	1	3113.84	4%
Superstructure						
Frame						
Glulam						
Timber - Glulam	Timber - GlueLam	568.78	m³	1	288.94	10%
Steel						
Steel - Section	Steel - Structural section incl fabrication	59.76	m³	1	466.16	10%
External walls						
Cladding						
Steel sandwich panel	Rockspan - 175mm (kg/m²)	2716.31	m²	1	73.72	0%
Curtain wall						
Glass - Glazed curtain walling	Flat Glass - by volume EPD	644.03	m²	0.012	19.32	1%
Curtain wall mullions						
Metals - Aluminium Mullions	Aluminium - extruded	1429.61	m	0.00115	4.44	10%
Roof						
Roof lights						
Rooflight	Lledo Rooflight	122.00	ea	1	2.44	0%

Items and Resources by Item category	User's Material Selection	Model Quantity		Geometry Conversion Factor	Mass (tonnes)	Wastage (%)
Timber Cassettes						
Insulation - Mineral Wool	Insulation - Mineral wool	1747.61	m³	1	61.17	15%
Paint - double coat	Paint - Double Coat (per m²)	10259.09	m²	1	21544.09	0%
Plastics - PVC	Plastics - PVC General	15.39	m³	1	20.47	5%
Timber - Birch Ply	Timber - Plywood	67.49	m³	1	47.24	10%
Timber - Glulam	Timber - GlueLam	568.78	m³	1	288.94	10%
Timber - SIPS Facing OSB	Timber - OSB sustainably sourced	168.68	m³	1	101.21	10%
Timber - softwood battens	Timber - Sawn Softwood	37.16	m³	1	18.02	10%
Internal walls and partitions						
Stud wall						
Plaster - Plasterboard	Gyproc WallBoard	172.56	m³	1	115.27	5%
Steel - Partition Studs	Steel - Light steel framing	2.42	m³	1	18.84	10%
Internal finishes						
Floor finishes						
Terrazzo						
Concrete - Screed	Mortar (1:5)	521.36	m³		990.58	20%
Concrete - Terrazzo Tiling	Terrazzo Tiles (CO2)	521.36	m³		1094.86	5%
Vinyl floor						
Plastics - Vinyl Flooring	Vinyl flooring	1.62	m³		2.11	5%

- Conversions to mass values shown are based on densities published in CIBSE Guide A **(2006)** and Geometric Conversion Factors shown, where Model Quantities are non-volumetric. For derivation of the Geometric Conversion Factors, see section 4.4.3.
- Wastage rates are based on data from the WRAP Net Waste Tool **(Waste and Resources Action Programme, 2013)**
- Bold text indicates the item categories based on the New Rules of Measurement
- Standard text indicates model objects taken off to the item catalogue.
- Italicised text indicates entries from the resource catalogue assigned to the item
- For details of the User's Material Selections and the associated carbon factors, Appendix E: and Appendix C:.
- PFA = pulverised fly ash

4.5.3.3 Results and Discussion

As with Case Study 4-1, the results of the embodied carbon assessment for Leicester North are presented in Figure 4-13 according the to the life cycle stage and according to building element and material in Figure 4-14 and Figure 4-15 respectively.

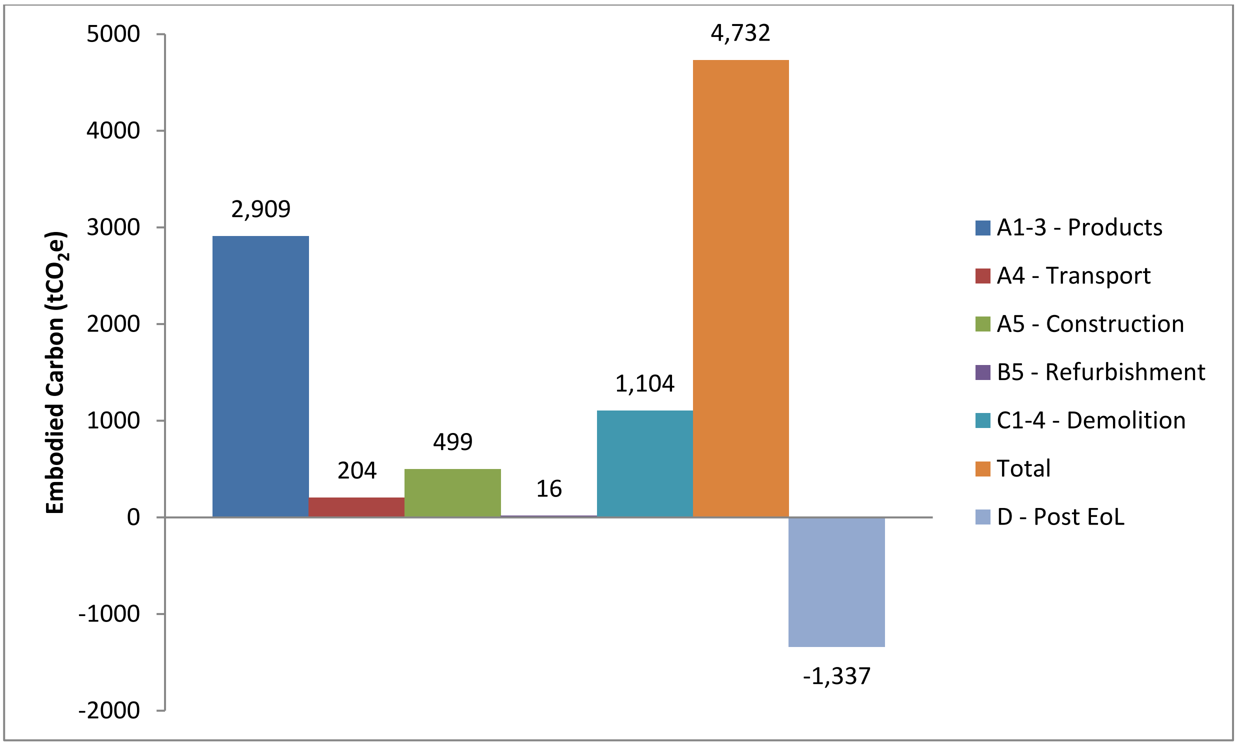


Figure 4-13: Embodied carbon of the Sainsbury's Leicester North by life cycle module (according to EN 15978 (British Standards Institution, 2011a))

The total embodied carbon of the sub and superstructure including the floor finishes is just over 4,700 tCO_2e. Whilst this is over 40% lower than the 60k Model assessed in Case Study 4-1, the scopes of the two assessments are different and so they should not be directly compared. In this assessment the fit out (shelving, chilled cabinets, services, etc.) were excluded, whilst they were included in Case Study 4-1. A comparison of the results for the substructure and superstructure of each of the three case study buildings is presented and discussed in section 4.6.

The distribution of the emissions between life cycle stages is comparable to Case Study 4-1 for Modules A1-3, A4 and A5. The exclusion of most of the fit out means that refurbishment (B5) contributes a negligible amount. On the other hand, end of life makes up a much greater proportion of the total. This was found to be due primarily to the large amounts of timber, which typically have higher end of life carbon factors than other materials. The reason for this is that in most of the assessments of timber, the sequestered carbon in the timber is shown as an emission at end of life stage. This is the case when timber is assumed to be incinerated, since the carbon is converted back to carbon dioxide in the combustion process. As discussed in section 4.5.2.3 above, any credit for energy recovery is allocated to the energy from waste plant operations and so only appears in module D here. Somewhat confusingly, the sequestered carbon is also shown as an emission at end of life if the timber is reused or recycled. The rationale for this is that the subsequent user of the timber can also claim a credit for the sequestered carbon without leading to double counting. This effectively, means the supermarket must pass on the credit for the carbon in the timber to the next user. These issues and the uncertainty that the different end of life scenarios introduce to the results are analysed and discussed further in Chapters 5 – 7. In particular, the rules for treatment of sequestered carbon in timber at the end of life are discussed in section 6.2.3.1.

The credits in module D for the benefits beyond end of life are equivalent to around 30% of the total cradle to grave embodied carbon. From Figure 4-14 it can be seen that the substructure, frame and roof make up around 24%, 54% and 19% of module D, respectively. From Figure 4-15 it can be seen that over three quarters of this is due to the recycling of steel (40%) and reuse of timber (36%).

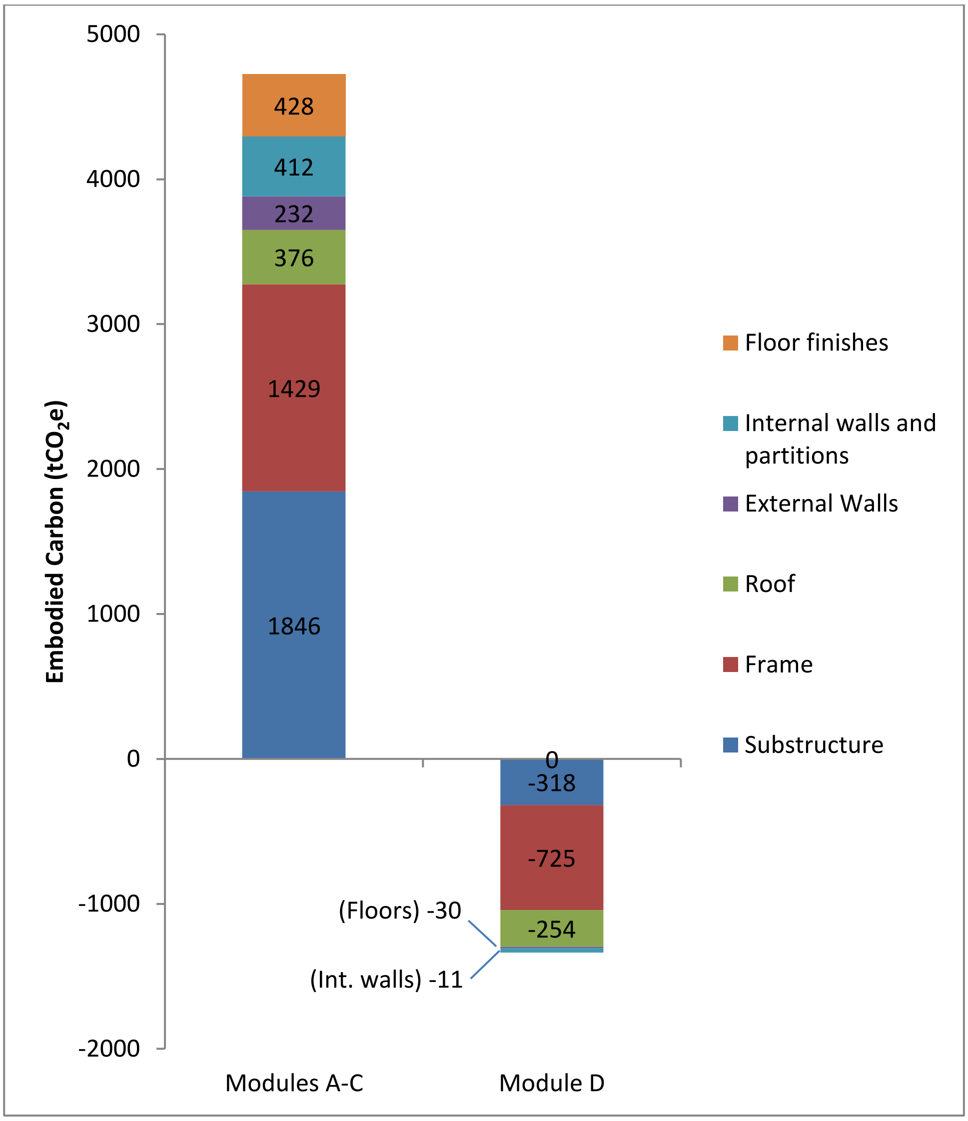


Figure 4-14: Embodied carbon of Sainsbury's Leicester North Store by building element for cradle to grave (Module A-C) and benefits beyond the end of life (Module D)

According to discussions with Sainsbury's, the choice of timber for the frame at Leicester North was primarily motivated by environmental considerations as well as aesthetics. It is therefore somewhat surprising that the frame for Leicester North has a significantly higher overall impact than that for the 60k Model which was entirely steel framed. This is due primarily to the larger size of the Leicester North building, both in terms of floor area and height. A direct comparison of the embodied carbon of steel and timber for the structural frame based on common floor area and column heights was undertaken as part of the later work on uncertainty. The results of this are presented and discussed in section 7.1 of Chapter 7.

Further comparisons of the Leicester North results with those of the other building case studies are presented and discussed in section 4.6 of this chapter.

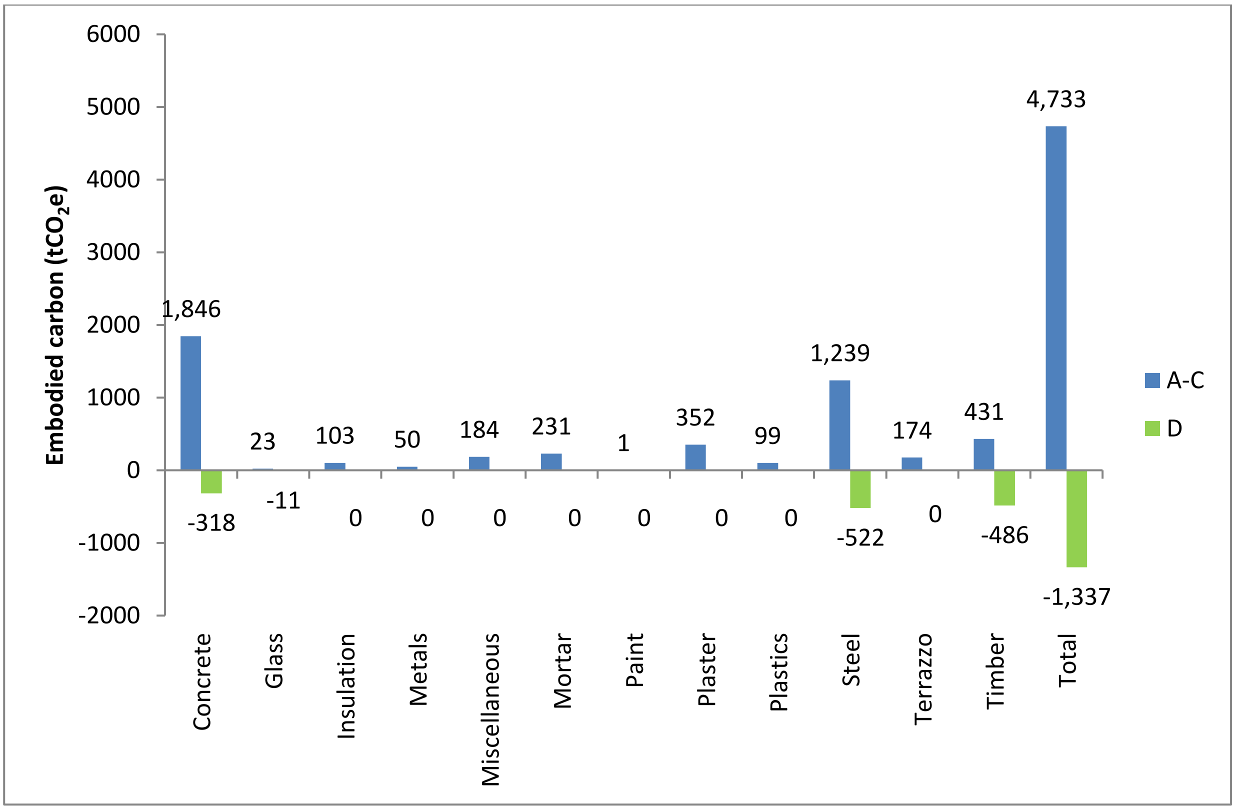


Figure 4-15: Embodied carbon of the Sainsbury's Leicester North by material

4.5.4 Case Study 4-3: Thanet

Sainsbury's Thanet is built in a configuration that is known within the business as a "store on stilts". This means the store is located above the car park. This arrangement has been used at Thanet, and elsewhere, because site constraints mean that locating the store at ground level with the car park adjacent is not feasible. This results in an eaves height which is two to three meters higher than the previous buildings in Case Studies 4-1 and 4-2, as can be seen in Table 4-15 below.

Table 4-15: Details of Sainsbury's Thanet Supermarket

Key Facts	
Gross Internal Area	11,241 m^2 (120,997 ft^2)
Sales Area	6,846 m^2 (73,692 ft^2)
Eaves Height:	
Sales	9.7 m (Car-park floor to ceiling height: 4.4 m)
Warehouse	7.5 m
Layout	Store on stilts
Frame	Steel
Roof	Composite insulated steel deck
Walls	Steel sandwich panels

4.5.4.1 Scope of the assessment

The BIM model available was comparable in scope to that of Leicester North in Case Study 4-2, in that it largely consisted of the structural and architectural elements of the design. A greater proportion of the external works were included in the model, presumably because the “store on stilts” configuration required the car park and service yard to be modelled since they are effectively part of the building. However, not all the necessary detail was available to extract quantities for these elements and so it was decided to exclude them entirely. This also allows more direct comparison with the other building case studies. The internal fit out was also excluded from the assessment due to a lack of detail. Therefore, the scope of this assessment was the sub-structure and super-structure and the internal floor and ceiling finishes.

4.5.4.2 Material quantities

The material quantities generated by the BIM QTO are presented in Table 4-16 in the same format as for the previous case studies. The calculation of material mass was undertaken in the same way (see table notes below or refer to section 4.5.2.2) Full details of the carbon factors for all the materials are given in Appendix F:.

Table 4-16: Material quantities for the substructure and superstructure of Sainsbury's Thanet, extracted from the BIM model.

Items and Resources by Item category	**User's Material Selection**	**Model Quantity**		**Geometry Conversion Factor**	**Mass (tonnes)**	**Wastage (%)**
Substructure						
Beams						
Concrete - poured reinforced concrete	Concrete - RC 30/37 (CEM I)	121.69	m³	1	279.88	4
Floor slab						
Concrete - floor slab	Concrete - RC 30/37 (CEM I)	2117.56	m³	1	4870.39	4
Pile foundations						
Concrete - poured reinforced concrete	Concrete - RC 30/37 (CEM I)	907.68	m³	1	2087.66	4
Pre-cast Beams						
Concrete - pre-cast reinforced	Concrete - RC 40/50 (CEM I)	39.49	m³	1	90.83	4
Retaining Wall - Blockwork						
Blockwork - 215mm Blockwork	Concrete Block -13 MPa	114.95	m³	1	241.38	20
Mortar - for Blocks	Mortar (1:5)	8.28	m³	1	15.74	20
Retaining Walls						
Concrete - poured reinforced concrete	Concrete - RC 30/37 (CEM I)	54.21	m³	1	124.68	4
Retaining walls - brick						
Brick	Brick - Brick EPD (BDA)	215.07	m³	1	333.37	20
Mortar - for bricks	Mortar (1:5)	30.19	m³	1	57.36	20
Superstructure						
Frame						
Steel						
Steel - Section	Steel - Structural section incl fabrication	145.36	m³	1	1141.08	10
Steel - Light Gauge Section	Steel - Coil (Sheet) - Darby	6.17	m³	1	48.47	10
Upper floors						
Composite Deck						
Concrete - floor slab	Concrete - RC 30/37 (CEM I)	2117.56	m³	1	4870.39	4
Steel - Profile Deck	Steel - Decking	12345.55	m²	0.00075	72.68	10
Floor slab						
Concrete - floor slab	Concrete - RC 30/37 (CEM I)	2117.56	m³	1	4870.39	4
Slab insulation						
Insulation - PU	Insulation - Polyurethane	1196.58	m³	1	73.15	15
External walls						
Cladding						
Steel sandwich panel	Rockspan - 175mm (kg/m²)	5280.45	m²	1	143.31	0
Curtain wall						
Glass - Glazed curtain walling	Flat Glass - by volume EPD	15.00	m³	1	37.51	1

Items and Resources by Item category	**User's Material Selection**	**Model Quantity**		**Geometry Conversion Factor**	**Mass (tonnes)**	**Wastage (%)**
Curtain wall mullions						
Metals - Aluminium Mullions	Aluminium - extruded - oekobaudat	2084.89	m	0.00115	6.47	10
Roof						
Cladding						
Insulation - PIR	Insulation - Polyurethane	1157.32	m³	1	73.15	15
Plastics - PVC	Plastics - PVC General	3.00	m³	1	3.99	5
Steel - Sheet	Steel - Coil (Sheet) - Darby	6.85	m³	1	53.79	10
Roof lights						
Lledo Rooflight	Lledo Rooflight	86.00	ea	1	1.72	0
Internal walls and partitions						
Stud wall						
Plaster - Plasterboard	Gyproc WallBoard	211.28	m³	1	147.60	5
Steel - Partition Studs	Steel - Light steel framing	2.90	m³	1	22.75	10
Internal finishes						
Ceiling finishes						
Ceiling tiles						
Plaster - Plasterboard	Gyproc WallBoard	9.67	m³	1	147.60	5
Plastics - PVC	Plastics - PVC General	3.00	m³	1	3.99	5
Floor finishes						
Terrazzo						
Concrete - Screed	Mortar (1:5)	397.78	m³	1	755.79	4
Terrazzo - Floor Tiling	Terrazzo Tiles (CO2)	207.84	m³	1	436.46	5
Tiled floor						
Ceramics - 6mm Tile - single sided	Ceramics - Tiles and Cladding Panels	0.31	m³	1	0.61	8
Vinyl floor						
Concrete - Screed	Mortar (1:5)	397.78	m³	1	755.79	4
Plastics - Vinyl Flooring	Vinyl flooring	2.16	m³	1	2.81	5

- Conversions to mass values shown are based on densities published in CIBSE Guide A **(2006)** and Geometric Conversion Factors shown, where Model Quantities are non-volumetric. For derivation of the Geometric Conversion Factors, see section 4.4.3.
- Wastage rates are based on data from the WRAP Net Waste Tool (Waste and Resources Action Programme, 2013)
- Bold text indicates the item categories based on the New Rules of Measurement
- Standard text indicates model objects taken off to the item catalogue.
- Italicised text indicates entries from the resource catalogue assigned to the item
- For details of the User's Material Selections and the associated carbon factors, Appendix F: and Appendix C:.
- PFA = pulverised fly ash

4.5.4.3 *Results and Discussion*

The results of Case Study 4-3 are presented in a similar format to the previous case studies with embodied carbon for the building broken down in according the to the life cycle stage in Figure 4-16 and according to building element and material in Figure 4-17 and Figure 4-18 respectively.

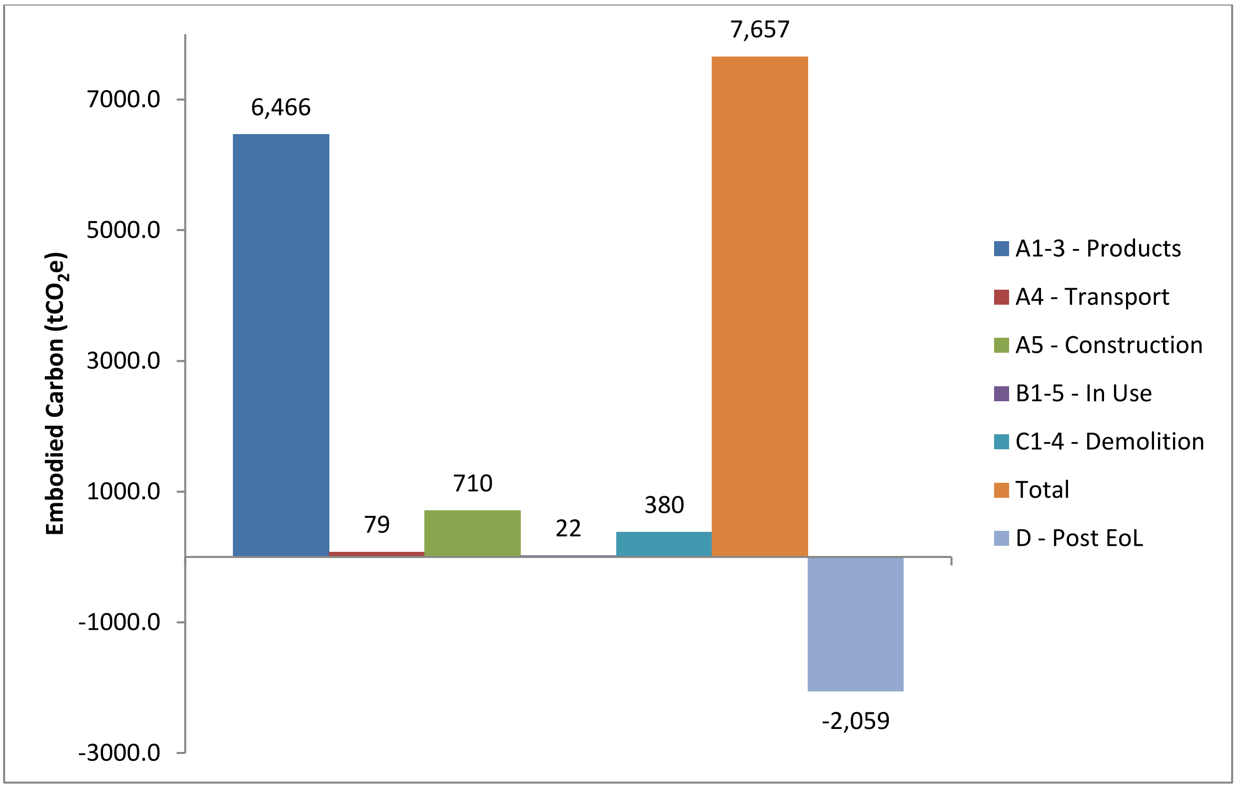


Figure 4-16: Embodied carbon of the Sainsbury's Thanet by life cycle module (according to EN 15978 (British Standards Institution, 2011a))

The “store on stilts” configuration results in an increase in the embodied carbon of the frame relative to the rest of the building when compared to the 60k Model, which was also steel framed. From Figure 4-10 in Case Study 4-1, the frame contributes 21.5% to the total when fit out items are excluded. For Thanet, the frame is responsible for 41% of the total embodied carbon. The additional steel required to raise the store above the car park is the primary driver of this difference. The steel quantities are equivalent to 106 kg/m^2 GIA. This is high even compared to benchmark figures for high rise buildings which are typically 75-95 kg/m^2, and is well above the 30-40 kg/m^2 benchmark for low rise, long span buildings (SteelConstruction.info, 2017). This is reflected in the benefit beyond end of life due to steel recycling. The total benefit shown in Figure 4-17 is 27% of the cradle to grave emissions compared to 15% for the 60k Model in Case Study 4-1.

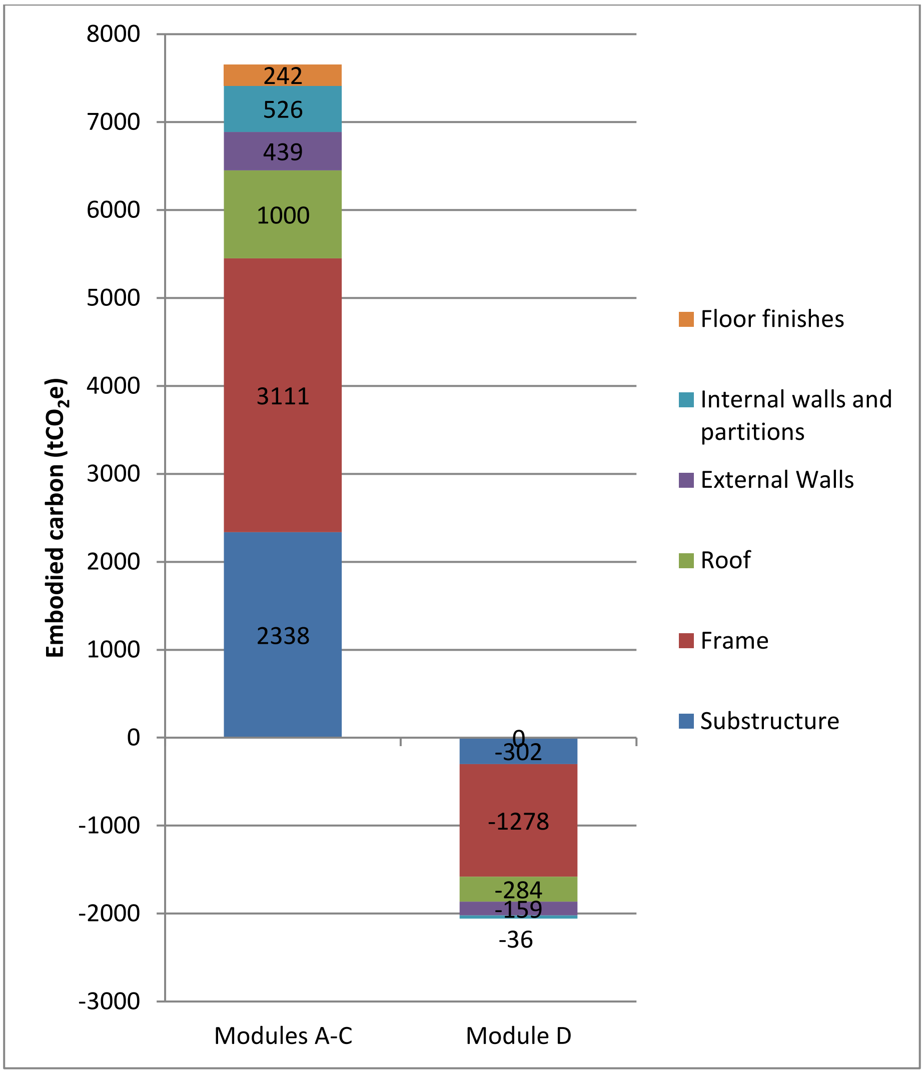


Figure 4-17: Embodied carbon of the Sainsbury's Thanet by building element for cradle to grave (Module A-C) and benefits beyond the end of life (Module D)

The increased use of steel is clearly seen in Figure 4-18 too. Also of note here is the high impact of concrete, which is greater than that for Leicester North in Case Study 4-2, despite Thanet having a lower overall volume of concrete compared to Leicester North. This is due to the use of pulverised fly ash in the concrete at Leicester North which, based on the data used in these assessments reduces the embodied carbon of the concrete. PFA is a by-product of coal fired electricity generation and in the data used here was deemed to have very low emissions. This is subject to some debate (Habert, 2013; Chen et al., 2010) and so the uncertainty affecting the embodied carbon factor of PFA and ground granulated blastfurnace slag (GGBS), another replacement for cement, is analysed further in the uncertainty assessments presented in Chapters 5-7.

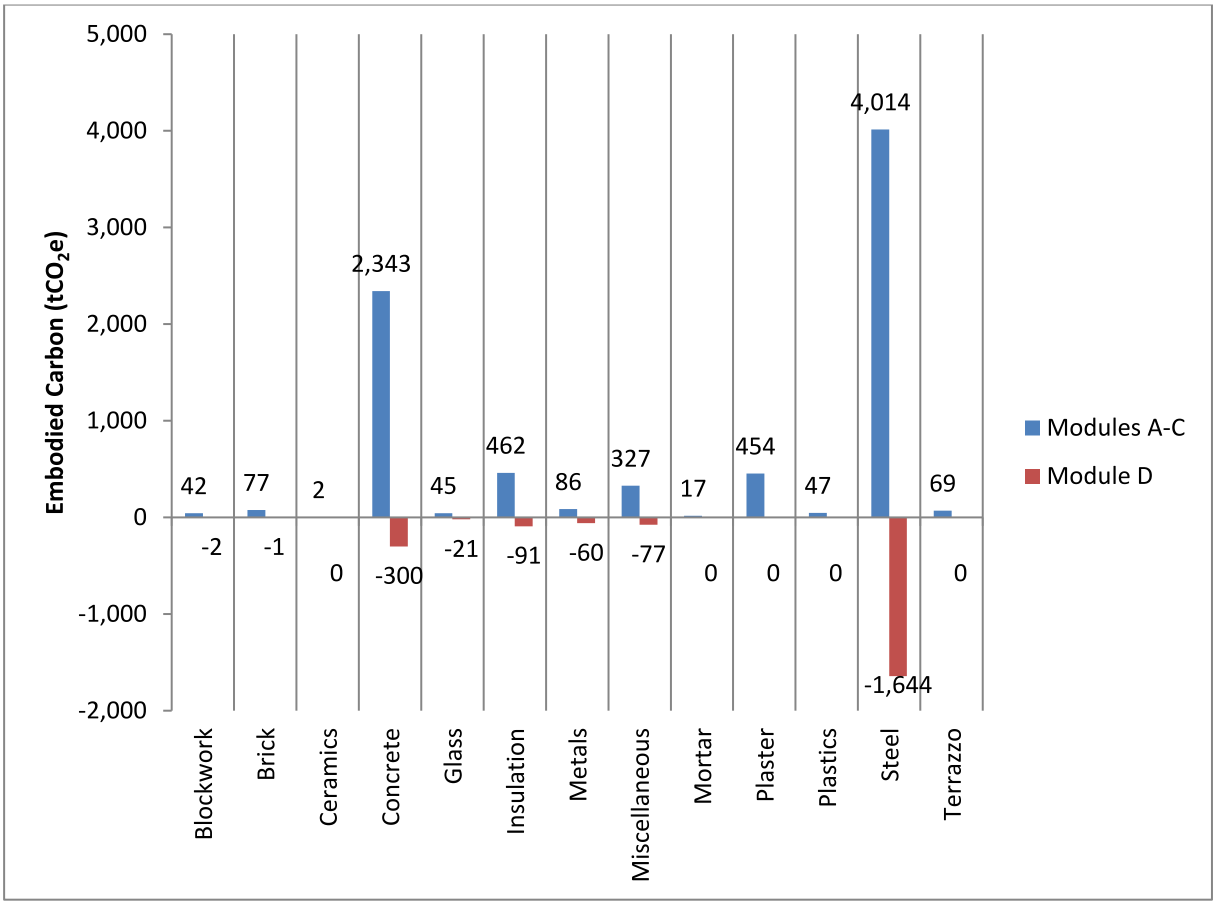


Figure 4-18: Embodied carbon of the Sainsbury's Thanet by material for cradle to grave (Module A-C) and benefits beyond the end of life (Module D)

4.6 Comparison and Discussion of Case Study Outcomes

In order to allow more direct comparison of the three building case studies, the embodied carbon results were normalised based on the floor area. In Figure 4-19, the results of the three buildings assessed here are shown in terms of the embodied carbon emissions per square meter of gross internal area. This can be considered to be the embodied carbon intensity for each of the building designs since it is the amount of carbon emitted to deliver each square meter of internal space.

As an additional comparison, the results of one of the previous assessments conducted for Sainsbury’s using a standard assessment process, i.e. based on manual QTO rather than using BIM have also been included. The scope of the assessments has been amended to allow like for like comparison. The embodied carbon of fit out items and of refurbishments has been excluded from all four sets of results to achieve this.

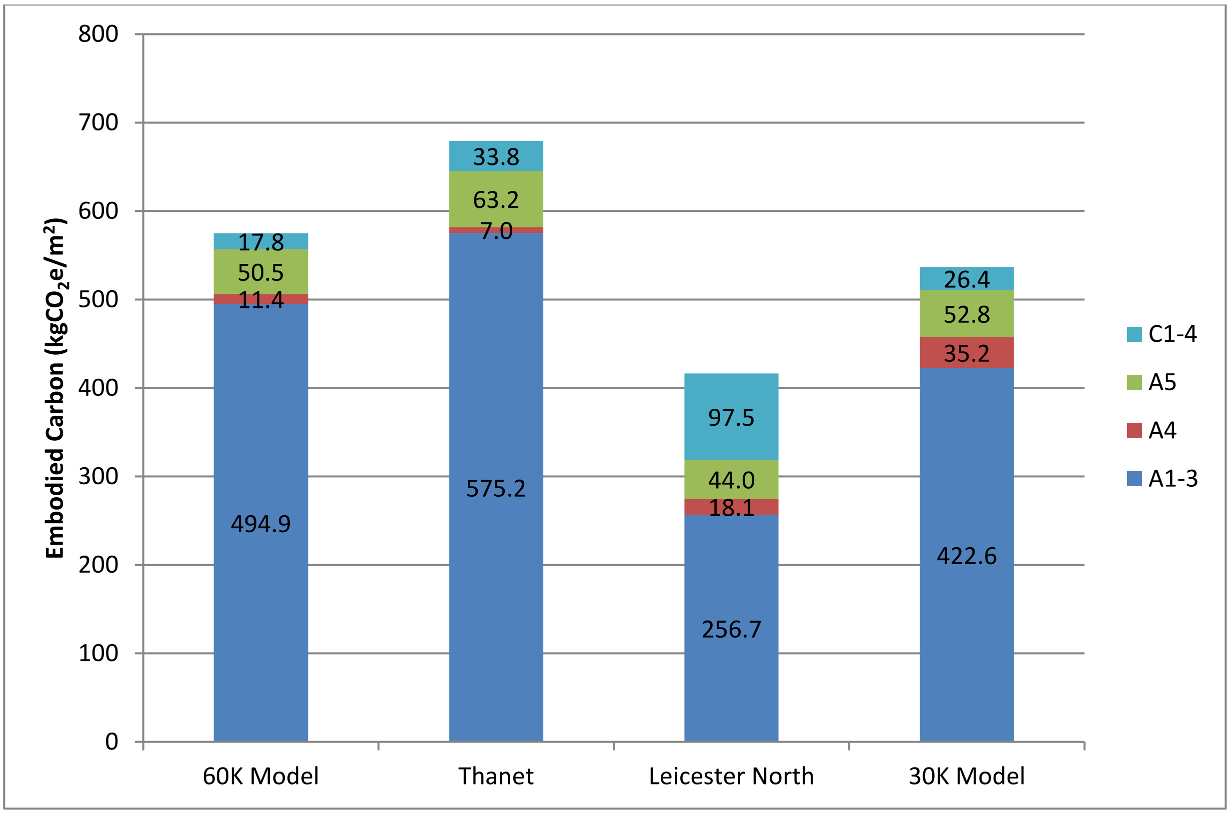


Figure 4-19: Embodied carbon relative to floor area for the 60k Model (as assessed in this research) and 30k Model (based on results of a prior assessment commissioned by Sainsbury's (dCarbon8, 2010))

The results from the previous assessment which was not part of this research are shown on the far right of the figure and relate to a different template store layout known as the 30k Model (dCarbon8, 2010). At 30,000 ft^2, the sales area of this model is half that of the 60k Model which was assessed in section 4.5.2 above. The configuration and construction of the 30k model is, otherwise, comparable to the 60k Model as detailed in Table 4-11.

The 30k Model appears to be less carbon intensive than the 60k Model. Without access to the underlying data and calculations, it is difficult to ascertain the reasons for this. According to the assessment report, the main source of data used was the Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011). For the two main materials that affect embodied carbon, concrete and steel, more up to date carbon factors have been used in this research. The carbon factors for steel in particular were higher than those given in the ICE. This is likely to be one of the main reasons for the different carbon intensity aside from variations in the material quantities for the two models.

The embodied carbon intensity of Thanet is almost 18% greater than the 60k Model. This reflects the higher volumes of steel required to achieve the "store on stilts" configuration. This is an important result for Sainsbury's and for other supermarkets. As the number of suitable sites for new stores diminishes, supermarkets are likely to start considering increasingly constrained locations. Data from Sainsbury's suggests that the "store on stilts" configuration was being more frequently employed in the period from 2008 than previously. The increased embodied carbon intensity of this arrangement should be a consideration when potential sites are being evaluated.

The significant reduction in embodied carbon intensity achieved at Leicester North is clearly shown. This is due, primarily, to the use of timber for the frame of the building and also the use of PFA in the concrete for the foundations. The increased use of timber also results in increased end of life emissions as has been discussed in section 4.5.3.3 above. If only the cradle to gate emissions are considered, then the carbon intensity of Leicester North is almost 50% less than that of the 60k Model. Yet when the other life cycle stages are included, this drops to just over a 25% reduction. This outcome supports the view of Moncaster and Song (2012) that all stages of the life cycle should be included the scope of the assessment. Key to achieving this is the improved availability of data for these life cycle stages which, despite some significant growth in the number of EPDs, continue to be less widely available than cradle to gate carbon factors.

The proportions of the total embodied carbon intensities that are attributed to each of the life cycle stages included in these results is broadly comparable for all four assessments. This reflects the similar underlying assumptions which were used when specific data were not available. This is particularly the case for construction (A5) where a factor of 10% of the cradle to gate emissions was applied in lieu of specific data (see section 4.4.2.3). Just 1% of the materials in the carbon factor dataset developed for this research had a value for this life cycle stage and hence the default value (10%) was used extensively in the assessments.

This lack of data for the carbon emissions of construction activities may be symptomatic of an underlying flaw in the approach adopted by the CEN TC 350 suite of standards. The standards promote the EPD as the basis for conducting environmental sustainability assessments (such as LCA or embodied carbon assessments) of buildings. As the literature review has highlighted, there is some consensus amongst researchers that the increased availability and use of EPD will address the lack of data which still persists. The data quality assessment of carbon factor sources conducted as part of this research (see Chapter 5) shows that experts in this field consider EPD data to provide high levels of data quality. However, the EPD approach is structured around assessing individual products. The EPD reviewed for this research were, without exception, produced by or on behalf of product manufacturers or their respective industry bodies. Yet the emissions arising from construction activities are not under the control of product manufacturers. Moreover, the assessment of these emissions would, in most cases, be likely to be conducted for an entire construction site. It is therefore hard to imagine how emissions data for a whole site could meaningfully be allocated to a single component. There are exceptions to this, and some activities on a construction site such as concrete pumping or crane operation during the erection of the frame, can very clearly be related to a specific material. Nevertheless, it is argued here that the continued lack of data for this life cycle stage suggests a different approach is needed. Emissions data for construction should be monitored at the site level and benchmarks and data produced for different types of building to allow more robust design stage embodied carbon assessments to be conducted.

4.7 Recommendations for Implementing BIM-integrated embodied carbon assessments

An approach to extracting quantity data from BIM for the purpose of conducting an embodied carbon assessment was developed and demonstrated using three case study supermarket buildings. A commonly defined set of material categories was used to create a means of semi-automatically linking material quantity and carbon factor data. In comparison to some previous work and existing commercially available tools, which have a limited built-in set of carbon (and environmental impact) factors, this approach allows for greater flexibility to incorporate data from the growing number of EPD for construction materials. The building case study results demonstrate that the approach can produce results which are comparable to those obtained when material quantities are produced manually. There are a number of limitations to Sainsbury's BIM models currently which mean that some of the quantity data extracted are not suitable for use in the embodied carbon assessment. These data require further manipulation or supplementary information in order to make them suitable for this purpose. The limitations identified in this research which reduce the suitability of the quantities data are:

- Simplified geometry
- Composite components not fully modelled
- Materials not specified to the required level of detail
- Quantities or dimensions not available
- Objects not clearly or not consistently named
- Duplicated objects (both within a single file and due to incorrect alignment of multi-file models)

By addressing some or all of these limitations, the ease with which embodied carbon assessments can be conducted using BIM data would be increased. The results of the building case studies have confirmed the conclusions of prior studies of supermarkets that concrete and steel are the two materials which contribute most to the embodied carbon. Therefore, priority should be given to addressing the above limitations where they affect these two materials.

For concrete, the lack of specification detail was the most common limitation. None of the concrete elements in any of the models reviewed had any indication of the strength class. In order to complete the embodied carbon calculations, typical concrete strength classes for each element of the building are required. The case studies conducted here were for existing buildings and one template design and it was possible to ascertain the actual concrete strength classes. When conducting assessments of buildings early in the design, where these details may not be available, it is recommended that typical strength class details be established and included in the BIM model meta-data.

For the steel in the buildings, the main limitation encountered was related to missing or simplified geometry. This was particularly true for steel items in the building envelope and fit out. To overcome this, it was necessary to include additional geometric conversion factors into the embodied carbon calculations based on manufacturer or supplier details.

One of the main barriers to achieving a fully integrated BIM embodied carbon assessment (or indeed an LCA) is the lack of any current means of automatically linking BIM objects to appropriate carbon factor data. The approach developed here was to create a common set of material categories which, when applied to both the quantity data and the embodied carbon data, facilitated semi-automation of the process of establishing this link. Thus the results of the research add weight to the argument for implementing a means of machine interpretation of the data stored in EPDs. Greater levels of automation may be achievable with more sophisticated categorisations of materials or through the use of emerging data management techniques such as semantic web technology.

5 Uncertainty Assessment of Embodied Carbon Factors: Development of Methods and Preparatory Work

The evidence from the literature review suggests that uncertainty is an important consideration in the assessment of embodied carbon of buildings. Much of the extant literature does not consider the effects of uncertainty. Uncertainty assessment methods, which have been developed in closely related fields such as environmental modelling and LCA, have not been widely applied in the field of embodied carbon. There are exceptions, and examples of these have been presented in section 2.7.4 of the literature review. Where uncertainty has been explicitly considered in embodied carbon research, the focus has been on using probabilistic assessment techniques. However, theories of uncertainty and conceptual uncertainty typologies have shown that environmental models such as LCA and embodied carbon assessments are subject to multiple types of uncertainty, some of which are not readily represented by probability functions or quantitative ranges. In other words, the probabilistic techniques that have been used to date have not sufficiently addressed the assessment and communication of these qualitative aspects of uncertainty.

This research has sought to address these limitations by conducting a comprehensive review of the sources of uncertainty that affect embodied carbon assessments and by assessing these according to an uncertainty typology which has been widely used in related fields. This allows for the selection and development of an uncertainty assessment method that is appropriate for the types and sources of uncertainty encountered. This preparatory work is described in section 5.3. The method presented has been specifically developed to assess the effect that uncertainty has when comparing the embodied carbon of different design alternatives. This is an application of the embodied carbon assessment method where uncertainty can introduce financial as well as environmental risks. Sainsbury's and businesses like it which seek to reduce embodied carbon, may wish to evaluate the cost and emissions reduction potential of several design alternatives, to identify the lowest cost per unit of carbon saved. Uncertainty in the estimates of embodied carbon emissions may result in these costs being over- or underestimated. The incorporation of uncertainty assessment into such comparative embodied carbon assessments provides a greater level of understanding of these risks. Hence there is also an important industrial application of the method and results presented in this chapter.

5.1 Summary of the Uncertainty Assessment Method

The uncertainty assessment method developed in this research, which has been outlined in Chapter 3, applies expert elicitation, literature based research, and scenario analysis to quantitatively and qualitatively assess the uncertainties that affect the estimation of embodied carbon factors for construction materials and products.

Expert elicitation is a structured procedure for capturing and recording the knowledge of experts in a particular field. In its application to uncertainty assessments of environmental models such as embodied carbon models, the objective is to elicit the experts' quantitative and qualitative judgements about uncertainties that affect the model formulation. These can be uncertain input data, uncertainty about the way the model is structured, or uncertainty about the assumptions on which the model is based (Walker et al., 2003). The format of the elicitations used in this research is described in section 5.3 and the results of the elicitations are presented and discussed in section 6.2. The uncertainty data elicited are then propagated through the embodied carbon model using quantitative techniques to evaluate their impact on the results. In other words, the results of the model are re-evaluated in light of the uncertainties identified within the model, leading to a range of possible embodied carbon values for the building rather than one single result.

Based on the literature review, scenario analysis was selected as a suitable quantitative technique to evaluate how these uncertainties affect the outcomes of comparative embodied carbon assessments of alternative materials for a specific function or element of the building.

The uncertainty assessment comprises three steps, which are identification, characterisation and communication (Van Asselt & Rotmans, 2002) as shown in Figure 3-2 on page 59. The outcomes of the identification step are presented in this chapter, followed by a description of the some of the preparatory work for the subsequent steps. Broadly, the characterisation part of the assessment is presented in Chapter 6 and the communication takes the form of the material comparison case study results, which are presented in Chapter 7. However, there is less of a clear distinction between these two steps and necessarily, in reporting the characterisation of uncertainties, communication is required.

5.2 Scope of the Uncertainty Assessment

As has been discussed in section 3.4 of the research methods chapter, it is important to consider the context in which the uncertainties are to be assessed. The chosen context for this research, based on Sainsbury's aims and requirements, is the use of embodied carbon assessment to support design decisions to reduce embodied carbon. Three case studies of alternative materials were chosen, to which the method was applied and therefore the scope of the uncertainty assessment is restricted to the materials relevant for these case studies. The case studies each compare the embodied carbon of two design alternatives for a given part of the building. Material substitution is a commonly cited approach to reducing the embodied carbon of buildings (Pomponi & Moncaster, 2016) and hence, in the selected case studies, the two alternative designs represent typical examples of such material substitutions which Sainsbury's has employed on past supermarket buildings. The material comparison case studies are based on data taken from the building case studies already presented in Chapter 4. Here, rather than modelling the whole buildings as has been done in Chapter 4, the scope of the embodied carbon assessments in each case study was reduced to the particular building element for which the two design alternatives are considered. The qualitative and quantitative data on uncertainty obtained through expert elicitation were then applied to the embodied carbon assessments of both design alternatives within each case study in order to model the effect that uncertainty has on each and, in particular on the predicted reduction in embodied carbon that can be achieved by choosing one design over another.

The material case studies that were selected are:

- Steel vs. glulam (structural engineered timber) for the structural frame
- Timber cassettes vs. composite metal deck for the roof
- Standard concrete vs. low carbon concrete for the floor slab

Hence, the materials that are included within the uncertainty assessment are:

- Steel (section and sheet)
- Timber (glulam, plywood, softwood, oriented strand board, and I-beams)
- Mineral wool insulation
- Polyurethane (PU) insulation
- Aggregates
- Cement
- Cement replacements (PFA and GGBS)
- Concrete

5.3 Preparatory Work

5.3.1 Identifying Sources of Uncertainty – The Uncertainty Matrix

The first step in the uncertainty assessment method is to identify sources of uncertainty. This was undertaken through a systematic literature review. The sources of uncertainty identified in the literature review (see section 2.7.5) were categorised using Walker et al.'s (2003) typology and associated uncertainty matrix which differentiates uncertainties according to their location, level and nature. The uncertainty matrix is reproduced in Figure 5-1 below and the sources of uncertainty identified within the uncertainty matrix are described and their categorisation discussed in sections 5.3.1.1 to 5.3.1.3.

		Level ***Nature***			
		Statistical		**Scenario**	
		Epistemic	***Variability***	***Epistemic***	***Variability***
Location	**Model Context**			• Allocation rules • System boundary • Time horizon of emissions • Level of data aggregation • Specification • Other methodological choices	
	Model Structure			• Functional unit	
	Model Inputs	• Measurement error • Transport • Energy Mix	• Process variation • Transport • Service life length • Maintenance / Refurbishment Frequency • Energy Mix • End of Life processing	• Geographic representative-ness • End of life processing	

Figure 5-1: Uncertainty matrix (after Walker et al., 2003) categorizing sources of uncertainty in embodied carbon assessments according to their nature, level and location

5.3.1.1 *Statistical Uncertainty*

Sources of statistical uncertainty are defined as those for which quantitative ranges can be determined (Warmink et al., 2010; Refsgaard et al., 2007; Walker et al., 2003). All the sources of statistical uncertainty identified here are located in the model inputs because they relate to uncertainties in carbon factors or material and energy quantities or both.

5.3.1.1.1 *Measurement error*

Measurement error affects the input data which are used to estimate carbon factors for materials and other types of data used to carry out an embodied carbon assessment of a building. It can have a number of causes such as imprecision or poor calibration of equipment or human error and can be random or systematic. Improved equipment and measurements methods can reduce measurement error, and hence this is an epistemic uncertainty.

5.3.1.1.2 Transport

Transport emissions can occur at multiple stages in the product life cycle. Data on transport emissions are a source of statistical uncertainty due to varying routes, different vehicle sizes and load factors. Improved collection of data would reduce this uncertainty to a degree, but cannot entirely eliminate fluctuations, for instance due to changing driving conditions which affect vehicle efficiency. Hence transport is listed as contributing both epistemic and variability uncertainty. There may also be scenario uncertainty if the location of particular processes in the life cycle is unknown (see 5.3.1.2 below).

5.3.1.1.3 Energy mix

Energy mix refers both to direct combustion of fuels on site, as well as consumption of electricity and relates both to energy used in the production stage as well as energy used in construction and demolition. The amount of energy used is a model input and uncertainty is introduced because the fuel mix and electricity source will vary by country and by supplier. In heavy industries such as steel manufacture, the fuel mix for a single supplier may also vary depending on price and availability. Even for smaller production facilities, which may not vary their fuel supply in this way, the grid factor of electricity is in constant flux and is usually averaged over a period of a year. As with transport emissions, there is both an epistemic and a variability aspect to the uncertainty introduced in the energy mix data.

5.3.1.1.4 Process Variation

Process variation in the manufacturing of a product affects the amount of energy, and possibly the amount of material required to make the product. It is therefore a source of uncertainty in the data used to estimate carbon factors for production and it may occur for a number of reasons. Between different producers or different production sites there is likely to be variation in levels of efficiency and process automation, and differences in the technologies and techniques applied. For some materials this uncertainty will be higher than for others because the processes are more variable. This uncertainty can, in theory at least, be reduced somewhat by obtaining more detailed information about the supply chain for a particular product and hence this is categorized as epistemic uncertainty.

Some materials have two or more highly distinct alternative production routes and in these cases, this gives rise to scenario rather than statistical uncertainty (see below).

5.3.1.1.5 Service Life Lengths

Service life lengths, of both individual components and the building as a whole, are inputs to the embodied carbon assessment of a building. It is possible to statistically assess the likely range of service life lengths of both products and buildings, provided the relevant data can be obtained. Hence, this is a source of epistemic statistical uncertainty.

5.3.1.1.6 Maintenance and Refurbishment Frequency

Maintenance and refurbishment frequency is a data input which affects the quantity of material used. It is closely related to the service life of building components. Likely frequency values can be determined from past data but these are subject to statistical uncertainty due to different maintenance approaches (e.g. preventative or reactive) and different operating conditions. This is not a source of uncertainty that can easily be reduced since some of the factors affecting maintenance and refurbishment frequencies are unknown. As such, this source of uncertainty has also been categorized as recognized ignorance.

5.3.1.2 Scenario Uncertainty

Scenario uncertainties are characterised by multiple alternative options where the likelihood of each occurring is unknown or where the options are not subject to probabilities but represent subjective choices. (Skinner, 2012)

5.3.1.2.1 Allocation Rules

Allocation rules are applied when a process produces multiple usable products. These rules determine how carbon emissions arising from the process are credited to each product. The main types of allocation are physical and economic. Under physical allocation, carbon emissions from a process are apportioned to each co-product arising from that process on the basis of physical properties such as mass or volume. Under economic allocation, the relative economic values of the co-products are used to determine the proportion of the total process emissions to allocate to each. Whilst standards such as EN 15804 and ISO 14044 provide guidance on appropriate selection of allocation method, there are nevertheless inconsistencies of approach between studies with different studies applying different allocation methods to the same processes. EN 15804 states that:

- Allocation shall be based on physical properties (e.g. mass, volume) when the difference in revenue from the co-products is low;
- In all other cases allocation shall be based on economic values;
- Material flows carrying specific inherent properties, e.g. energy content, elementary composition (e.g. biogenic carbon content), shall always be allocated reflecting the physical flows, irrespective of the allocation chosen for the process.

A low or small difference in revenue between co-products is further defined as being less than 25%. (British Standards Institution, 2014a, p. 29).

For example, if a process results in two products, A and B, and product A generates 50% more revenue than product B, then the emissions should be allocated by economic value. In this example, since the ratio of economic value of product A to product B is 1.5:1, the carbon emissions should be allocated to products A and B by the same ratio. If the ratio were 1.2:1, that is, only 20% difference in revenue, then according to EN 15804 physical allocation should be applied. The standard does not include clear justification of how this 25% cut-off has been determined nor how economic value should be determined when co-products must undergo further separate processing in order to be considered a tradeable material. Such additional clarity would reduce the scope for alternative interpretations and application of the guidance, an example of which is discussed below.

Material flows with specific inherent properties are to be treated separately from the allocation of process emissions. This applies, for example, to carbon sequestered in timber. Timber production processes often have two or more co-products (Rüter & Diederichs, 2012) which may have a high difference in revenue such as sawn solid timber and wood trimmings for use in manufactured boards. In this case, EN15804 requires that process emissions be allocated on economic value. However, the biogenic or sequestered carbon in the timber must still be allocated by mass. For example, the production of 1 cubic meter (approximately 480 kg) of sawn softwood produces around 1.04 cubic meters (approximately 500 kg) of co-product (Rüter & Diederichs, 2012 Table 3.2.2.C). If the co-product has an economic value of 15% of the value of the sawn timber (an arbitrary figure for illustrative purposes), then 15% of the process emissions are allocated to the co-product and 85% to the sawn timber. By contrast, the sequestered or biogenic carbon is allocated by mass. The sequestered carbon for the initial 2.04 cubic meters of timber would be around 1.5 tonnes of CO_2e (British Standards Institution, 2014b). Hence both the co-product and the sawn timber are allocated a credit of approximately 0.75 tonnes of CO_2. In fact, the co-product is allocated marginally more of the sequestered carbon than the sawn timber by a ratio of 5:4.8.

Structural steel is one example of where these allocation rules have not been consistently interpreted. The EPD for structural steel section and plate from the German industry body, Bauforumstahl e.V., uses physical allocation principles for allocating impacts to the by-products of iron and steel production, stating:

> Unless justified the methodology is based on physical allocation […]. The aim of the methodology is to separate the involved processes, functional or causal. Economic allocation was considered, as slag is considered a low-value co-product under /EN 15804/, however, as neither hot metal nor slag are tradable products upon leaving the [blast furnace], economic allocation would most likely be based on estimates. Similarly [basic oxygen furnace] slag must undergo processing before being used as a clinker or cement substitute. (Institut Bauen und Umwelt e.V., 2013, p. 5)

The quote refers to two types of slag; that which is produced during reduction of iron ore into pig iron (blast furnace slag) and slag produced in the further processing of pig iron into steel (basic oxygen furnace slag). The emissions from these two processes are, according to this statement, allocated between the steel and the slags on the basis of physical properties. It is not made clear in the EPD cited here, nor in any of the others reviewed, what physical properties have been used.

The explanation is unfortunately rather brief and, by referring to both physical allocation as well as the separation of involved processes, appears to make contradictory assertions. The guidance for co-products in EN 15804 states that 'allocation shall be avoided as far as possible by dividing the unit process to be allocated into different sub-processes' (British Standards Institution, 2014a, p. 28). Only where such sub-division is not possible, is allocation permitted and in such cases economic or physical allocation is selected according to the rules previously quoted above. Therefore the stated aim to separate processes involved, whilst consistent with EN 15804, would, if achievable for all co-products, avoid the need for allocation of any kind. Therefore the use of physical allocation may suggest that such sub-division was not possible. Similar justifications for physical allocation are given in other EPD for steel products (Ruukki, 2014; Institut Bauen und Umwelt e.V., 2014a), despite this apparent inconsistency.

By contrast, Darby estimates that GGBS has an economic value of just 4% of the value of steel, and concludes that 'based on the requirements of BS EN 15804 allocation should be on the basis of economic value.' (Darby, 2014, p. 53).

The choice of allocation method will affect the resulting carbon factor, and these different values represent discrete alternatives rather than a range of possible values which could be quantified using a statistical distribution. Hence this represents a source of scenario uncertainty.

5.3.1.2.2 System Boundary

The system boundary defines the scope of the assessment upon which a carbon factor for a product or an embodied carbon estimate of a building is based. Material and energy flows beyond the system boundary are not part of the assessment. For material or product carbon factors, examples of such exclusions which could be applied are the embodied carbon of capital equipment used in the manufacturing process or fuel consumption for staff commuting. One of the most important and controversial choices relating to the system boundary is the treatment of loads (carbon emissions) and benefits (avoided emissions) arising from recycling and reuse (Jones, 2009). Different system boundaries represent discrete choices. Carbon factors for one material estimated using two different system boundaries may vary significantly and this discrete variation cannot be meaningfully represented as a statistical range.

5.3.1.2.3 Time Horizon of Emissions

Time horizon of emissions refers to the length of time over which the global warming potential of greenhouse gas emissions in the atmosphere is assessed. Because different greenhouse gases remain in the atmosphere for different lengths of time, assessing their impact over different timescales changes their relative contribution to global warming. The most widely adopted approach is the 100 year time horizon (Shine, 2009). This has been criticised as arbitrary and for not placing sufficient importance on impacts occurring in the distant future (Fearnside, 2002). Whilst it would, theoretically, be possible to mathematically model the change in a carbon factor as the time horizon is varied, examples of this have not been found in the literature on embodied carbon. So time horizon is, effectively a scenario uncertainty. However, despite the criticisms of the 100-year time horizon, it has been almost universally adopted in LCA and embodied carbon research and therefore, the decision was taken to exclude this from the scope of the assessment in this research.

5.3.1.2.4 Level of Data Aggregation

The level of data aggregation ranges from carbon factors that have been calculated for a generic material based on global average production to supplier specific factors for a particular product. Between these extremes, there are examples of carbon factors for materials based on average production data for a specific country (e.g. many of the factors in the ICE database by Hammond & Jones, 2011) or for a specific group of suppliers (e.g. the EPD for structural steel released by Institut Bauen und Umwelt e.V., 2013). In general, data are typically either aggregated for multiple production sites operated by a single company, or across multiple companies or by country or region. The choice of the appropriate level of aggregation is sometimes a pragmatic one, for example groups of producers may choose to collaborate and produce an aggregated EPD (or other form of embodied carbon data source) in order to share the cost associated with data gathering, producing and externally verifying the results. There can also be rational justification for aggregating data at a particular level, for example with globally traded commodities such as metals, where it has been argued that data should be aggregated at the global level (Darby, 2014; Hammond & Jones, 2011; Jones, 2009). These different levels of aggregation are discrete choices and lead to discrete differences in results. This is therefore categorised as a source of scenario uncertainty.

5.3.1.2.5 Functional Unit

The functional unit defines the amount of product for which emissions are reported based on the function that the product performs and where this is a physical parameter such as mass, volume or area this is known as the declared unit (British Standards Institution, 2014a). The use of different functional units will give different results and this could be considered a source of scenario uncertainty. However, for this research, functional unit has been excluded from the scope of the uncertainty assessment on the basis that if the functional unit is known, it is possible to convert data from one functional unit to another and thus ensure consistency.

5.3.1.2.6 End of Life Processes

End of Life processes describe which waste treatment process will be applied to a particular material or product after it is removed from the building. In general, the possible treatments are re-use, recycling, incineration, energy recovery, and disposal to landfill. For a given material, it is possible to ascertain current practice in the UK, however, since the end of life for the building will be several decades into the future, what will occur then is a source of scenario uncertainty.

5.3.1.3 ***Recognized Ignorance***

Beyond the level of scenario uncertainty, Walker et al. use the term recognised ignorance, which they define as ‘fundamental uncertainty about the mechanisms and functional relationships being studied’. Whilst scenario uncertainties are characterised by alternatives outcomes of unknown likelihood, recognized ignorance refers to unknown outcome.

By definition, recognized ignorance is something that cannot be evaluated or quantified directly. However Funtowicz and Ravetz (1990) proposed that evaluating data quality can provide an indication of which parts of a model are most subject to recognized ignorance. They argue that by evaluating the quality of the underlying knowledge which underpins a particular set of data, it is possible to assess where the boundaries of ignorance lie.

5.3.2 Data Quality Matrix

The term data quality refers to features of data that affect its reliability and its applicability for a given use (Weidema & Wesnæs, 1996) The data quality matrix (sometimes called a pedigree matrix – see section 2.7.3 of the literature review and 3.3.1 of the research methods) is a tool for evaluating these qualitative features in a semi-quantitative way. Data are scored against criteria that have been identified as important for the particular field of research. In this research, the data quality matrix was applied to evaluate, using expert judgement, the data quality of commonly used sources of carbon factor data. Ranking these sources in this way, and prioritizing the use of data from sources deemed to have higher data quality provides a means of reducing the effects of recognized ignorance on the embodied carbon assessment.

The sources of carbon factor data chosen for evaluation are based on the findings of the literature review and are as follows:

- Factor derived/aggregated from literature review
- Industry data – e.g. carbon factors provided by a product supplier or industry body but which are not published as part of an EPD
- Government data – generic carbon factors provided by national governments, such as those released by Defra (2015) for use by UK organisations compiling annual carbon emission reports
- Factor from a commercial LCA database such as GaBi or Ecoinvent Factor from a PAS 2050 compliant carbon footprint
- PAS 2050 Carbon Footprint
- Factor from an EPD (EN 15804 compliant)

In the data quality matrix developed and used in this research, the different sources of carbon factors are assessed against four data quality criteria. The chosen data quality criteria were adapted from those proposed by Risbey et al. (2006, pp. 12–13) and applied by Van Gijlswijk et al. (2003) for assessing data quality in emissions inventories. The four data quality criteria are described below with the descriptions adapted from those in Risbey et al. (2006, p. 12) and including examples specific to embodied carbon factors of materials:

Table 5-1: Descriptions of the four data quality criteria used in the data quality matrix shown in Figure 5-2 (based on Risbey, Sluijs, & Ravetz, 2006, p. 12)

Data Quality Criterion	Description
What is being measured/estimated?	Data used to estimate carbon factors are not always measured directly but are in some cases derived from a related quantity called a proxy. Examples of common proxies for carbon emissions are fuel and electricity consumption data. This first data quality criterion requires an evaluation of how closely the proxy correlates to the desired data. Where exact measures are used, so that no proxy is necessary, the data would receive the highest score of 4.
Reliability / Empirical basis	Data may be directly measured, or based on assumptions or an extrapolation from a smaller dataset, or it may be modelled data. In terms of empirical quality, direct measurements score highest, whilst modelled data and estimates are of lower quality. This criterion is assessed independently of whether the data that has been collected is proxy data or a measure of the desired quantity (e.g. volume or mass of CO_2). Whilst proxy data would not achieve the maximum score for the first data quality criterion (What is being measured/estimated), if the proxy data used is based on direct measurements, it should none-the-less achieve a high score for this second criterion of data quality.
Method	The method of data collection also has a bearing on its quality. Rigorous and well established methods with appropriate checks and verification are scored highly. If there are conflicting views on whether a method is suitable or which of two or more alternative methods is preferred, this would lead to a lower score. The descriptor makes it clear that even if a particular expert considers the method employed to be appropriate but is aware of conflicting views, they should still award the lower score.
Validation	Validation here refers to whether the data has been checked against independent sources. Validation against an independent set of data is deemed to be preferable to internal validation and so receives a higher score. Data that has been validated by comparing it to a proxy for the same measure would receive a lower score for this criterion than data that has been validated against independent data for the same variable.

The matrix is shown in Figure 5-2 including examples which were provided to participants to help clarify the meaning of the descriptors for a particular score.

		Data Quality Criteria			
		What is being measured / estimated	**Reliability / Empirical basis**	**Method**	**Validation**
Data Quality Score	**4**	**Exact Measure** E.g. CO_2 sensors monitoring flue gases	**Data from direct measurements** Irrespective of whether a proxy is being used – e.g. fuel consumption measured for an entire site	**Best available practice**	**Compared with independent measurements of same variable**
	3	**Approximate measure** E.g. CO_2 sensor used to monitor a test rig and then extrapolated	**Data from measurements with some assumptions** e.g. Fuel consumption measured for a site for a particular period and then extrapolated to a longer time-frame	**Reliable method commonly accepted**	**Compared with independent measurements of closely related variable**
	2	**Proxy with good correlation** e.g. Fuel consumption as a proxy for CO_2 emissions	**Modelled/derived data** e.g. Fuel consumption modelled based on published engine efficiencies – no direct site measurement	**Acceptable method but limited consensus on reliability**	**Compared with measurements – not independent**
	1	**Proxy with weak correlation**	**Qualified estimates/rule of thumb**	**Preliminary methods with unknown reliability**	**Weak/indirect validation**
	0	**Proxy not clearly correlated**	**Crude speculation**	**No discernible rigor**	**No validation or validation not known**

Figure 5-2: Data Quality Matrix for evaluating the quality of common sources of carbon factor data used in embodied carbon assessments (adapted from Risbey et al., 2006)

5.3.3 Expert Elicitation Format

Expert elicitations can be conducted in a group setting with several experts present, or individually via interviews or questionnaires (Skinner, 2012, p. 34). Each of these formats has advantages and disadvantages. In a group setting, experts can be briefed together, thus allowing for a common understanding of the aims, objectives and terminology. Potential drawbacks of the group format include the possibility that certain participants dominate the discussions and that experts are influenced by the views of other participants(Cooke & Goossens, 1999). This might lead to results which do not fully reflect the diversity of opinion on a particular issue. Conducting the elicitations individually prevents interaction and discussion between experts, mitigating the influence they have on each other and this may reveal greater diversity of opinion. However there may be insights that are revealed through discussions between experts and conducting individual elicitations do not allow for this. Furthermore, each expert must be individually briefed and so points of clarification are not necessarily shared with other experts. Thus using the individual format, there is the increased possibility that the experts interpret the questions and tasks in different ways.

Only very limited evidence was found in the literature to support the selection of one format in preference to any other. Cooke and Probst report on the discussions from the *Expert Elicitation Policy Symposium and Technical Workshop* which took place in Washington D.C. in 2006. The symposium delegates are reported as being unanimously in favour of individual assessments, primarily ‘to avoid effects of dominant or vocal participants’ (2006, p. 16). However, no details of the number or experience of the delegates involved is provided in their report. Slottje et al. (2008) discuss the question of elicitation format, and suggest that there are advantages and disadvantages to both. Without a robust basis on which to select one format in preference to the other, it was decided that both approaches would be applied. A first round of elicitations was conducted in a group setting and a second round was carried out in the form of individual interviews with experts.

Knol et al. (2010) propose that a structured, iterative approach be applied for expert elicitation. They argue that the use of a formalised elicitation protocol can help to ensure results are reliable and repeatable. Moreover, an iterative approach to the process allows for the possibility that the outcomes from one elicitation process may reveal new information which requires a reframing of the elicitation questions or a refining of the procedure in some way. The group elicitation session was therefore exploratory in nature and the outcomes were used to inform the design of the protocol for the second set of individual elicitations.

5.3.3.1 First Phase Elicitation Plan and Protocol

The preliminary elicitations were conducted using a group format in order to exploit the advantages of that format which are discussed in 5.3.3 above. The drawbacks of the group format, could be mitigated, firstly by asking the experts to complete some steps of the elicitation on their own, without discussion, and secondly by using individual interviews for the second set of elicitations

The objectives defined for the preliminary elicitations were as follows:

- To elicit expert views on the sources and types of uncertainty encountered in embodied carbon assessments of buildings
- To elicit expert judgements on the data quality of a range of different sources of carbon factor data
- To elicit preliminary quantitative estimates of uncertainty ranges for the carbon factors of a number of materials commonly used in the structure and envelope of supermarkets.

The elicitation protocol developed to achieve these objectives consisted of five steps which are listed in Table 5-2 along with a description of the purpose and anticipated outcomes of each:

Table 5-2: Structured elicitation protocol used in the preliminary round of expert elicitations held on Tuesday 01 May 2016 at Sainsbury's Store Support Centre, London

Step	Description	Purpose / Anticipated Outcome
1	Prior to attending the group elicitation session, participants review a briefing document and complete questionnaire (See Appendix G:)	Experts will familiarise themselves with the elicitation objectives and the questions they will be asked. Data on indicators of expertise are collected from the questionnaire
2	Briefing presentation covering: a. basic theory of uncertainty b. explanation of the elicitation tasks c. explanation of common biases in quantitative elicitation	Establish common understanding of uncertainty. Equip experts to avoid bias in their judgements
3	Elicitation of list of key sources of uncertainty	Sources identified by experts are combined with those identified by literature review and categorised in the uncertainty matrix. Used to identify suitable methods for subsequent stages of the uncertainty assessment

4	Elicitation of quantitative uncertainty estimates for carbon factors of pre-determined materials	Quantitative estimates of uncertainty ranges for case study materials from each expert; to be used to conduct explorative quantitative uncertainty assessments and to identify suitable methods for subsequent stages of the uncertainty assessment
5	Elicitation of data quality scores for sources of carbon factor data	Used to determine a rank or preference of sources of carbon factor data for use in the case studies.

The briefing presentation and the first of the elicitation tasks, to identify key sources of uncertainty (step 3), were conducted with all participants together in one group in order to establish a common understanding of the objectives and definition of uncertainty. The subsequent elicitation tasks were carried out individually.

5.3.3.2 Second Phase Elicitation Plan and Protocol

The second set of elicitations was conducted with experts individually in the form of semi-structured interviews. This format was chosen in preference to a questionnaire in order to allow for the interviewer to better ensure that the interviewee had fully understood the questions and tasks they were being asked to complete. Where possible, interviews were conducted face to face, however, for practical reasons some of the interviews were conducted via internet based video conferences.

Based on the outcomes of the first phase group elicitations, an adapted protocol was designed for the second phase interviews whereby experts were asked to consider scenario and statistical uncertainties separately. Each expert was asked to complete the elicitations for a selection of the case study materials, as agreed with them in advance on the basis of their field of expertise, particularly their familiarity with the production processes for a given material. This was judged either on the basis of their current and previous employment (i.e. if they had worked within the relevant field of industry and whether they had) or on their previous publications where available.

The objectives defined for the individual elicitations were as follows:

- To elicit qualitative judgements of the types of scenario uncertainty affecting specific materials.
- To elicit quantitative judgements of the statistical uncertainty affecting specific materials.

The elicitation protocol developed to achieve these objectives consisted of five steps which are listed in Table 5-3 along with a description of the purpose and anticipated outcomes of each:

Table 5-3: Structured elicitation protocol used in the second phase individual expert elicitation interviews

Step	Description	Purpose / Anticipated Outcome
1	Prior to the elicitation session, participants review a briefing document and complete questionnaire (See Appendix G:)	Experts will familiarise themselves with the elicitation objectives and the questions they will be asked. Data on indicators of expertise are collected from the questionnaire
2	Expert is briefed on the elicitation procedure	
3	The expert and interviewer discuss sources of uncertainty affecting embodied carbon of the materials under consideration	Establish common understanding of uncertainty.
4	Elicitation of list of key sources of uncertainty	Sources of uncertainty relevant to embodied carbon assessment are identified by experts and later categorised in the uncertainty matrix. Used to identify suitable methods for subsequent stages of the uncertainty assessment
5	Elicitation of quantitative uncertainty estimates for carbon factors of pre-determined materials	Quantitative estimates of uncertainty ranges for case study materials from each expert; will be used to conduct explorative quantitative uncertainty assessments and to identify suitable methods for subsequent stages of the uncertainty assessment
6	Elicitation of data quality scores for various sources of carbon factor data	Used to prioritise the selection of different possible sources of carbon factor data for a given material in the embodied carbon assessments undertaken throughout the research

5.3.3.2.1 Elicitation of Scenario Uncertainty

The relevant sources of scenario uncertainty identified in the uncertainty matrix in Figure 5-1, are as follows:

- Allocation rules
- System boundary
- Time horizon of emissions – excluded from the uncertainty assessment (see 5.3.1.2.3)
- Level of data aggregation
- Other methodological choices
- Functional unit – excluded from the uncertainty assessment (see 5.3.1.2.5)
- Geographic representativeness
- End of life processing

Based on a review of the literature, the specific sources of scenario uncertainty relevant to each of the materials included in the scope of this uncertainty assessment were identified along with the possible alternative choices for each. For example, for steel, the choice of system boundary (with reference to how recycling is accounted for) was identified as a key source of scenario uncertainty (World Steel Association, 2011; Jones, 2009). The main alternatives presented in the literature were the cut-off approach, also known as the recycled content approach, and the system expansion or closed loop approach (See section 6.2.2.2 for further explanation). For each material, the scenario uncertainties identified were depicted as a set of decisions in the form of a decision tree diagram. An initial diagram was produced based on the literature and these were then presented to the expert during the individual elicitation interview. The expert was asked to comment on whether and how they would change the diagram. The experts' individual responses were recorded and for each material, the responses from the two or three relevant elicitations were combined to produce a revised diagram. Figure 5-3 shows an example of the decision tree diagram that was produced for steel based on the scenario uncertainties identified in the literature. The decision nodes (diamond shaped) depict specific choices or assumptions that must be made in order to estimate the embodied carbon of steel whilst the rectangular boxes show the different alternative options that can be chosen. The text across the top of the figure references the material specific source of uncertainty to the general sources of uncertainty identified in the uncertainty matrix in Figure 5-1 in section 5.3.1.

System Boundary | Geographical Representativeness | Level of Data Aggregation

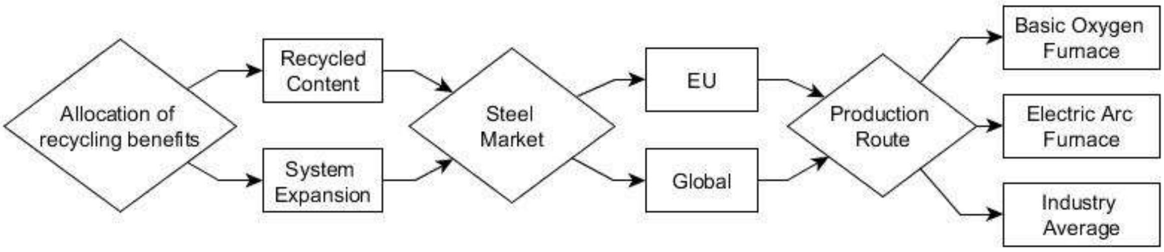


Figure 5-3: Example decision tree depicting scenario uncertainties affecting the embodied carbon value of steel.

The adapted (post elicitation) diagrams for all the materials assessed are presented and discussed in the results in section 6.2.

5.3.3.2.2 Elicitation of Statistical Uncertainty

The statistical uncertainties identified in the uncertainty matrix in Figure 5-1, and described in section 5.3.1.1, are those sources of uncertainty whose effect can be quantitatively defined by an uncertainty range for a given input parameter to the embodied carbon model. This characteristic differentiates them from the scenario uncertainties described in Section 5.3.1.2, for which such quantitative ranges are difficult to determine or not appropriate.

Quantitative estimates of the uncertainty range due to statistical uncertainties were elicited from the experts during interview using an adapted form of that trialled in the group elicitations. The experts were advised to exclude from their estimate any variability due to the scenario uncertainties already identified using the decision trees and to provide their subjective view of the remaining uncertainty in a carbon factor calculated according to a given set of assumptions and methodological choices.

An iterative procedure, based on an approach recommended by Slottje et al. (2008) was used to elicit estimates of the statistical uncertainty ranges. The expert participant was presented with pair-wise alternatives of uncertainty ranges in the form of a percentage variation above and below a carbon factor. The actual carbon factor value was not specified by the interviewer in order to not bias the participant. However, if they wished to specify a particular carbon factor value when considering their responses, they were free to do so.

At each iteration of the process, the pairs of alternatives were progressively adjusted based on the experts' choice at the previous iteration until an uncertainty range was reached that the expert felt most confidently was representative of the likely statistical uncertainty. An example of how the first three pairs of alternatives would be formulated based on different responses is presented in Figure 5-4 below.

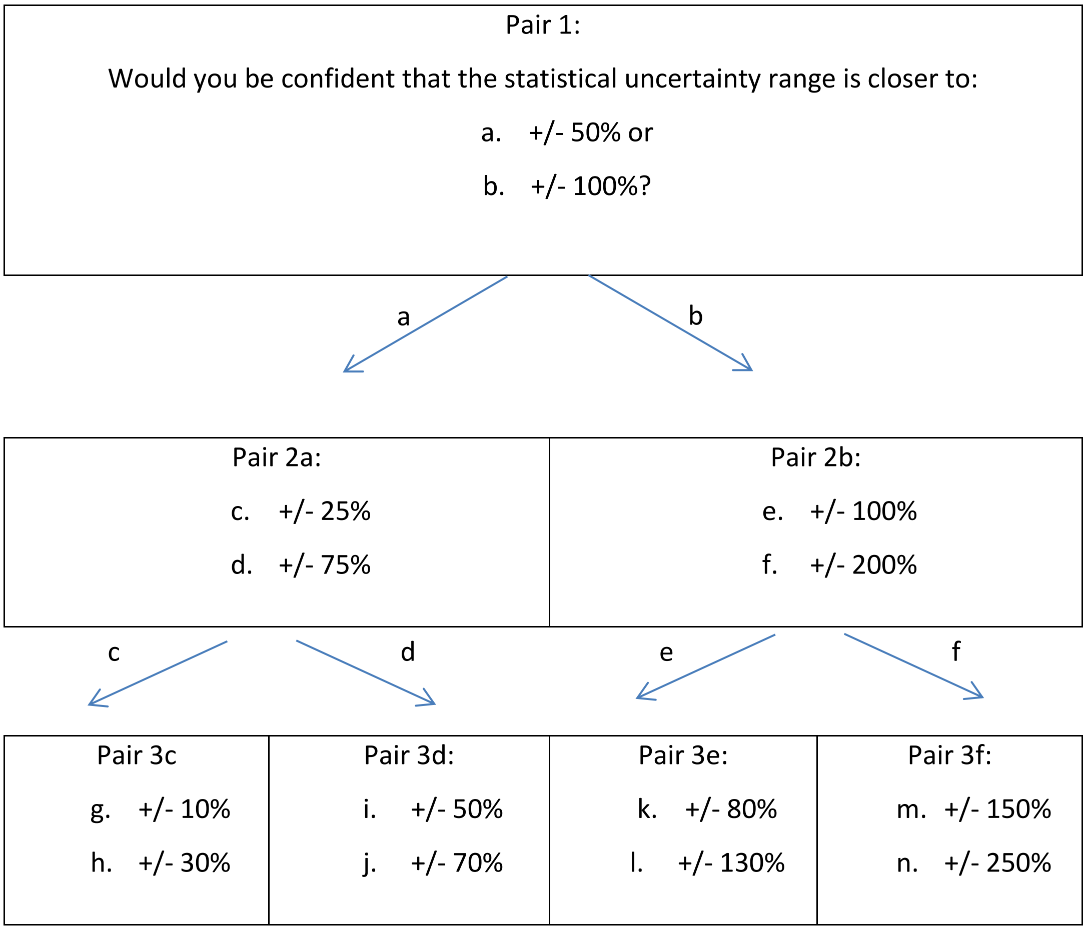


Figure 5-4: Illustrative example of the possible combinations of pair-wise alternatives presented to each expert to elicit their subjective estimate of the statistical uncertainty affecting the embodied carbon factor of a given material

Once the expert had settled on a range, they were then asked to comment on whether they thought that the range would be equally distributed or whether the range might be skewed positively or negatively. In other words, if they think it more likely that a carbon factor could be higher than the published value than that it would be lower, or vice versa.

Estimates of statistical uncertainty were elicited in this way for the materials that the expert had agreed in advance to cover in the elicitation interview. In addition to the quantitative estimate, qualitative comments made by the expert about their confidence levels or general comments about statistical uncertainty were recorded.

5.3.4 Expert Selection

In applying expert elicitation, the aim is to obtain and use the knowledge of a number of experts in a given field. In this regard, it differs from methods such as surveys or questionnaires which are typically applied to establish the views of a representative sample of a population or group. Expertise, rather than representativeness or sample size, is what supports the validity and defensibility of the outcomes of expert elicitation. Expertise ‘refers to performance in a particular domain […] that is superior to the performance of a number of other people within that same domain’ (Schvaneveldt et al., 1985, p. 699). Hoffman states that ‘the accumulation of skill based on experience and practice are key’ to the development of expertise. For this research, the required expertise was in the field of embodied carbon assessment of buildings and construction products. The criteria for selecting experts were therefore based on measures of experience and practice within this field. Cooke and Goossens propose that the following factors be considered when selecting participants for expert elicitations:

- reputation in the field of interest
- experimental experience in the field of interest
- number and quality of publications in the field of interest
- diversity in background
- awards received
- balance of views
- interest in and availability for the project (1999, p. 29)

These principles were used to guide the selection process in this research. Existing professional and academic networks were used to identify potential participants. Invitations were sent to people whom the research team (consisting of doctoral student, two academic supervisors and one industry supervisor) had prior connection with and who were known to have expertise in the field of embodied carbon. The invited experts were also given the opportunity to nominate further colleagues whom they felt had suitable expertise. In order to achieve a balance of views, experts from academia and industry were included, although restrictions on availability of invited participants meant that it was not possible to achieve an equal representation of both. All the participants of the group elicitation were invited to participate in the subsequent individual elicitations. However, as can be seen from the tables below, only one participant was available to participate in both sets of elicitations. Table 5-4 and Table 5-5 provide a list of the participants, summarising their background and experience.

Table 5-4: Details of the expertise of participants in the group elicitation of uncertainty

Participant	Relevant qualifications / publications	Years of relevant experience	Studies conducted	Field
A	Doctoral thesis, peer reviewed journal papers and industry publications	5	5-10	Academic
B*	Doctoral thesis, peer reviewed journal papers, industry guidance	17	unknown	Industry
C	MSc	5	None	Industry
D	Diploma, industry publications and guidance	18	50+	Industry
E	Industry qualification in building sustainability assessment	4	5-10	Industry
F*	Industry qualification in low carbon design	10	unknown	Industry
G	Book contributor	6	10-20	Industry
H	Peer reviewed journal papers	3	<5	Academic
I	Peer reviewed journal papers	3	10-20	Academic
J	Industry guidance	10	10-20	Industry

* Participants B and F did not complete the pre-elicitation questionnaire and so their years of experience is estimated based on when they completed their highest academic qualification.

Table 5-5: Details of the expertise of participants in the individual elicitations

Participant	Relevant qualifications / publications	Years of experience	Studies conducted	Field	Materials
A	See Table 5-4				Steel, Concrete, Timber,
J	Industry guidance	10	10-20	Industry	Steel
K	PhD in embodied carbon related field	6	10-20	Academic	Timber, Concrete
L	PhD in embodied carbon related field	25	Unknown	Industry	Concrete
M	MSc, Industry certification in low energy building design	13	Unknown	Industry	Insulants
O	PhD in embodied carbon related field	11	Unknown	Industry	Insulants
P	PhD in embodied carbon related field	12	Unknown	Industry	Insulants
Q	Member of industry standards committee for LCA	26	Unknown	Industry	Steel

* Participants L-Q did not complete the pre-elicitation questionnaire and so their years of experience is estimated based on when they completed their highest academic qualification.

The range of experience measured in years of professional and/or academic practice was between 3 and 26. Of the participants who completed the questionnaire, all but one had conducted one or more quantitative embodied carbon assessments in the past. Participant C had, at the time of attending the group elicitation session, not conducted such an assessment whilst participants B, F and L-Q did not complete the questionnaire. However, the experience of these participants was known to at least one member of the research team. Based on knowledge of their work related to embodied carbon and a review of their academic and professional qualifications and, where applicable, their publications, they were judged to have an appropriate level of expertise.

The individual elicitations each involved assessing up to three of the materials from the material comparison case studies. The materials to be included in each elicitation were agreed in advance with the expert and these are listed in Table 5-5. Table 5-6 lists this information by material and highlights that only two expert elicitations were conducted which covered timber.

Table 5-6: Materials included in the scope of the uncertainty assessment showing which expert participants were consulted during the individual elicitations

Material	Participant
Steel	A, J, Q
Timber	A, K
Concrete (including aggregates, cement and cement replacements)	A, K, L
Insulants (Mineral Wool and PIR/PUR)	M, O, P

A third participant (P) had been chosen from those listed to assess timber but the time allocated to the elicitation was only adequate to cover three materials and so timber was not covered. Due to time constraints it was not possible to identify an additional expert and arrange and conduct a further elicitation. The results of the elicitations and the subsequent material comparison case studies are presented in Chapters 6 and 7 respectively. The outcomes and methods, including the implications of expert availability for the results, are discussed further in Chapter 8 (see section 8.3).

6 Uncertainty Assessment of Embodied Carbon Factors

The assessment of uncertainty comprises three stages; identification, characterisation and communication (see section 3.4). The identification stage and outcomes have been described in Chapter 5. In this chapter, the characterisation stage and outcomes are detailed and discussed. This characterisation is conducted by combining three methods; expert elicitation, literature based study, and scenario analysis.

Elicitations were conducted to assess and evaluate the data quality of different sources of published carbon factors. The types of uncertainty that affect the embodied carbon factors of selected materials were also elicited. These two outcomes of the elicitations were used to guide detailed literature based research to identify a range of carbon factors for each material. Using these carbon factors, the resultant uncertainty in the embodied carbon of each material was then evaluated using scenario analysis. The results of the elicitations and the carbon factor ranges derived from the literature are presented and discussed in this chapter.

The uncertainty assessment was conducted in this way for the following eight materials:

- steel,
- timber (covering five different types – see section 6.2.3 and Chapter 7),
- mineral wool insulation,
- polyurethane insulation,
- aggregates,
- cement,
- supplementary cementitious materials (PFA and GGBS)
- and concrete.

These were chosen based on the material comparisons selected for the case studies which are presented in Chapter 7.

6.1 Data Quality Assessment Using the Data Quality Matrix

In the elicitations, experts used the data quality matrix shown in Figure 5-2 to assign scores to each of six different sources of carbon factors using four data quality criteria. The six sources of carbon factor data evaluated were:

- Factor derived/aggregated from literature review
- Industry data – e.g. carbon factors provided by a product supplier or industry body but which are not published as part of an EPD
- Government data – generic carbon factors provided by national governments, such as those released by the UK Department for Environment, Agriculture and Rural Affairs (2015) for use by organisations compiling annual carbon emission reports
- Factor from a commercial LCA database such as GaBi or Ecoinvent
- Factor from a PAS 2050 compliant carbon footprint
- Factor from an EPD (EN 15804 compliant)

An example response from participant A is shown in Table 6-1 below. The aggregated score is unweighted and is therefore the mean of the participant's four scores for that data source.

Table 6-1: Data quality scores elicited from participant A

	Data Quality Scores for Data Sources:					
Data Quality Criteria	Literature	Industry Data	Govt. Data	Commercial LCA	PAS2050 Carbon Footprint	EPD
What is measured	1	2	2	2	2	2
Reliability	1	3	2	3	2	3
Method	0	1	3	4	2	3
Validation	1	2	2	4	1	2
Aggregated Score	0.75	2	2.25	3.25	1.75	2.5

The full set of data quality scores from all 10 participants in the group expert elicitation session are reproduced in Appendix H:. The data quality scores for each of the four data quality criteria and the aggregated score from all 10 experts were averaged and these averaged results are presented in Figure 6-1 below.

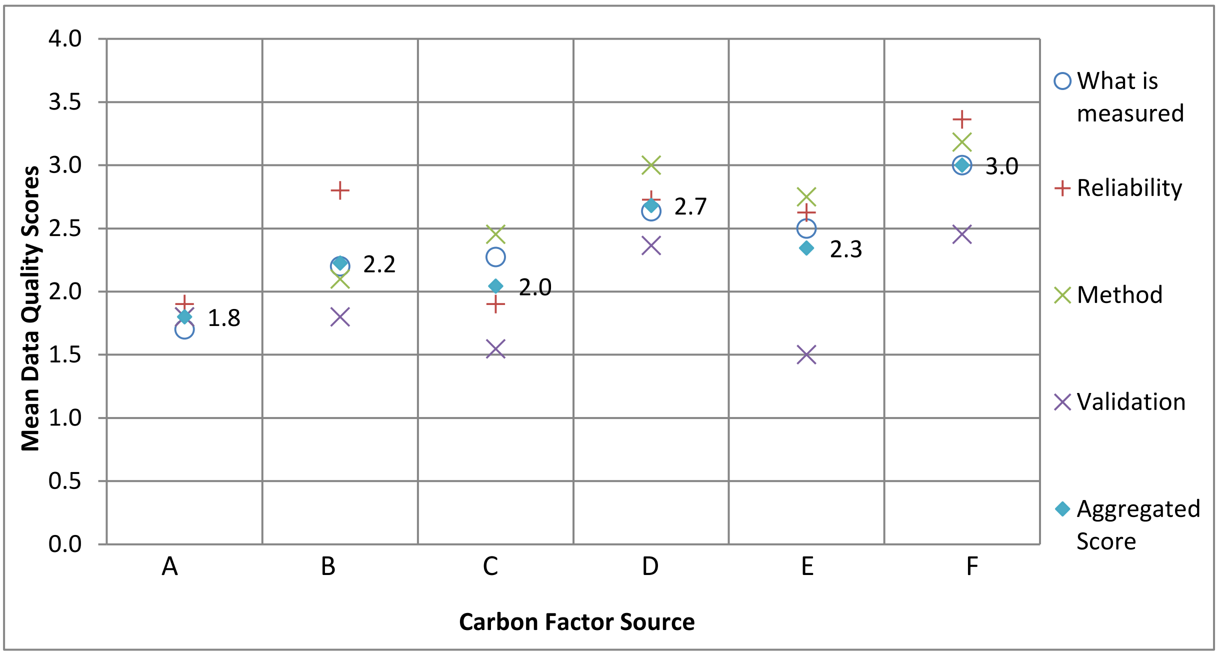


Figure 6-1: Mean data quality scores for different sources of carbon factor data elicited from experts using the data quality matrix in Figure 5-1.

Table 6-2: Standard deviation for data quality scores from experts

Source:	**A**	**B**	**C**	**D**	**E**	**F**
What is measured	0.8	0.4	0.4	0.6	0.5	0.9
Reliability	0.8	0.6	0.5	0.7	0.7	0.5
Method	0.8	0.7	0.7	0.9	0.4	0.7
Validation	1.3	1.1	0.8	1.2	0.9	1.4

Table 6-2 presents the standard deviation of the 10 participants' scores for each data source and each data quality criterion. Despite the small sample size, comparing the standard deviation provides an indication of the level of consensus between the 10 participants for each of the data quality criteria, relative to the other criteria and the other data sources. The higher the standard deviation for a given criterion, the greater the range there was between the scores elicited from the 10 participants.

The results in Figure 6-1 show that of the six sources of carbon factor data, EPD scored most highly for all criteria, with an average, aggregated data quality score of 3.0. Data from commercial LCA had the second highest aggregated score, although the average score for the reliability criterion was lower than that of industry data. Carbon factors derived from literature have the lowest aggregated data quality score, although this source scored more highly, on average, for the validation criterion than both government data and PAS2050 carbon footprint data.

For all six sources of carbon factor, validation was the lowest scoring of the four data quality criteria. However, it also displays the least consensus amongst experts; standard deviations of the scores from all 10 experts for a given carbon factor source are higher for validation than for the other criteria. This outcome suggests two possible conclusions, which are not mutually exclusive. Firstly, the experts may have different understandings of how validation is carried out for each of these sources of carbon data, which could be caused by poor documentation of validation approaches or because the experts have not had need to investigate and evaluate validation techniques for some or all of these data sources. Secondly, the experts may have interpreted the descriptors for the different scores shown in the data quality matrix in Figure 5-2 in different ways. In order to investigate whether either or both of these are true, it would have been necessary to undertake some form of discussion or formal consensus finding exercise with the experts. However, since the data quality scores were analysed after the workshop, this would have required follow up discussions with the same participants. Only one of the participants who attended the first elicitation workshop was also available for the second round of individual elicitations. The issue of expert availability and its potential impact on the results is discussed further in Chapter 8 (see section 8.3.2.3).

The results do allow a clear ranking of these six sources of carbon factor according to their perceived data quality; this is shown in Table 6-3. The ranking in Table 6-3 provides a basis from which to prioritise sources of carbon factors that were used to derive uncertainty ranges in the latter sections of this chapter.

Table 6-3: Sources of carbon factors ranked according to the average aggregated data quality score elicited during the first workshop held on 01 March 2016

Rank	**Source**	**Mean Aggregated Data Quality Score**
1	F - EPD (EN 15804 compliant)	3.0
2	D - Factor from commercial LCA database	2.7
3	E - PAS 2050 compliant carbon footprint	2.3
4	B - Industry data	2.2
5	C - Government data	2.0
6	A - Factor derived/aggregated from literature	1.8

This ranking was applied both to the building level assessments which are presented in Chapter 4 and to the case studies of comparative assessments presented later in this chapter. The elicited scores and their implications for the use and further development of each of the different sources of carbon factors are discussed in section 8.2.3 of Chapter 8.

6.2 Scenario and Statistical Uncertainties for Case Study Materials

The different assumptions and choices giving rise to scenario uncertainties were depicted graphically in the form of a decision tree. An initial decision tree was produced for each material based on a review of relevant literature. During the individual elicitations, the experts were shown these initial decision trees for the materials that they had agreed to include in the scope of their elicitation and were asked to amend or add to them based on their knowledge of the material and its embodied carbon. The diagrams were then amended to incorporate the judgments of the two or three experts who commented on each. These adapted decision trees are presented and discussed in the following sections. The decision trees depict the material specific sources of scenario uncertainty. Using these elicited scenarios, a quantitative uncertainty range was derived for each of the materials under consideration from one of the six carbon factor sources according to data quality ranking shown in Table 6-3. This uncertainty range is then propagated through the embodied carbon model using scenario analysis. The total number of scenarios for the scenario analysis of each material is determined by the number of possible paths through the decision tree. This is shown beneath each decision tree diagram in the subsequent sections.

For each material, carbon factors were then sought or derived to match each of the scenarios represented by the decision trees. Each scenario represents one possible combination of assumptions and choices that affect the embodied carbon of that material. Together, these scenarios represent the scenario uncertainty for that material. By identifying or deriving a carbon factor which corresponds to each set of assumptions and choices it was then possible to calculate the resultant embodied carbon for the case study material for all scenarios. In this way, the scenario uncertainties are propagated through the embodied carbon model so that their effect on the results can be evaluated. Many of the decision nodes in the diagrams relate to a particular aspect of the life cycle of that material. For example, the allocation of co-products from steel affects only the production or the cradle to gate carbon emissions for steel. The modularity principle set out in EN 15804 (British Standards Institution, 2014a) means that EPDs present carbon factors and other environmental impacts for different parts or modules of the life cycle separately. By applying this modularity principle, it is possible to specify different carbon factors for a given module to reflect the scenario uncertainties that affect that part of the life cycle.

After assessing scenario uncertainties using the decision trees, each participant was then asked to estimate the effect of statistical uncertainties using the technique described in Section 5.3.3.2.2. The results of this part of the elicitation procedure for all materials are displayed below in Table 6-4 to allow comparison. The results for each individual material and the combined impact of both statistical and scenario uncertainties on the carbon factors for that material are then presented in Sections 6.2.2 – 6.2.6.

6.2.1 Statistical Uncertainty Results

The elicited statistical uncertainty ranges are reported as upper and lower bounds. Where experts stated that they expected the uncertainty range to be equally distributed, the absolute values (i.e. the modulus) of the upper and lower bounds are equal. Where the expert felt that the range would not be equally distributed, this is shown by the different value for the upper and lower bound.

Table 6-4: Estimates of the statistical uncertainty ranges for embodied carbon factors of selected construction materials elicited by semi-structured interview from nine experts

		Statistical Uncertainty Estimate	
Material	Participant	Lower Bound	Upper Bound
Steel	A	-15	15
	J	-	-
	Q	-10	30
Timber	A	-15	15
	K	-20	20
Concrete	A	-15	15
	K	-20	20
	L	0	10-25
Insulants (Mineral Wool and PU)	O	-20	20
	P	-	-

PU = Polyurethane
Where no value is provided, this indicates that the participant was unable or unwilling to provide an estimate

Of the experts who responded, all judged statistical uncertainty to be less than 30% with six of the seven experts estimating the uncertainty range to be within +/- 30% but not less than a range of +/- 10%. Five of the elicited ranges are equally distributed, whilst participant Q and L both estimated that the upper bound of statistical uncertainty would be greater than the lower bound. Both participants justified this on the basis that they expect published carbon factors to be optimistic, reflecting a best case or close to best case value.

Two participants were unwilling to make estimates because they felt they could not do so with confidence. Based on the criteria that have been used as indicators of expertise in this research, namely years of experience and relevant qualifications or publications, these two experts appear to have no less expertise than those who were willing to provide estimates.

6.2.1.1 Validation of Statistical Uncertainty Estimates

Few uncertainty assessments have been undertaken for embodied carbon and no examples have been found that treat scenario and statistical uncertainty separately as has been done here. This limits the possibility to validate the experts' estimates in Table 6-4. The Inventory of Carbon and Energy (ICE) (Hammond & Jones, 2011), which is one of the most comprehensive reviews of embodied energy and carbon factors published to date, includes indicative uncertainty ranges for some materials. However, the ranges given are for embodied energy rather than embodied carbon and do not separate scenario and statistical uncertainty. The relevant ranges from the ICE are shown in

Table 6-5: Uncertainty ranges for embodied energy of selected materials from the Inventory of Carbon and Energy (Hammond & Jones, 2011)

Material	Uncertainty Range
Steel	+/- 30%
Timber	
Glulam	+17% to -33%
Plywood	+33% to -33%
Softwood	+76% to -90%
OSB	No data
Insulants	
Mineral Wool	+/- 40%
	+37% to -19%
Concrete	+/- 30%
Aggregates	+201% to -40%
Cement	+/-30%

The ranges from the ICE data are all higher than those elicited for this research in Table 6-4. This would be expected given that they do not distinguish different levels of uncertainty. The ICE ranges are expected to include the effects of both statistical and scenario uncertainties. The ranges for aggregates and softwood are notably greater than the other materials, though no reason is provided for this.

For timber, the statistical uncertainty ranges estimated in this research were compared to those presented by Rüter and Diederichs (2012) for the variability in GWP of different types of timber. Since their ranges are based on their own inventory data and results, it may be assumed that common assumptions and methods have been used. If this assumption is valid, then the ranges they present, which are reproduced in would represent only sources of statistical uncertainty.

Table 6-6: Uncertainty ranges for embodied carbon of different types of timber product (Rüter & Diederichs, 2012)

Material	Uncertainty Range
Glulam	+63% to -41%
Plywood	+80% to -24%
Softwood	+83% to -35%
OSB	No data

Comparing the ranges in Table 6-4 and Table 6-6 suggests that the estimates elicited from experts in the interviews conducted for this research may underestimate the actual variation due to statistical uncertainty. These should therefore be seen as preliminary estimates and this serves to highlight the need for greater availability and transparency of uncertainty data for the embodied carbon factors of different materials.

For the following uncertainty assessments of carbon factors for the eight materials selected, the elicited values are used. Where estimates differed between experts, these were combined so as to give the greatest overall range. For example, for steel the statistical uncertainty range applied in the assessment in the following section was +30% to -15% which is a combination of the responses from participants A and Q.

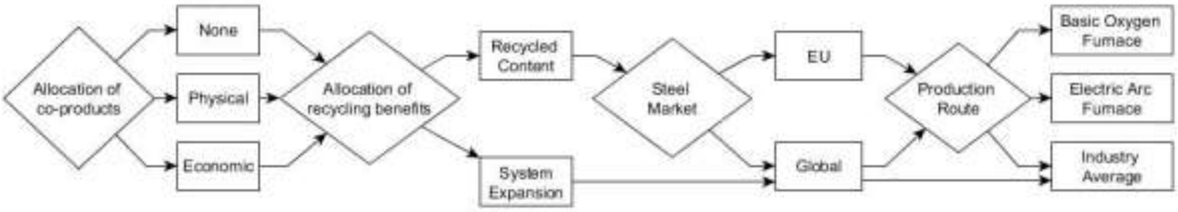
6.2.2 Steel

Steel is manufactured in one of three ways, the basic oxygen furnace (BOF) route, the electric arc furnace (EAF) route and the open hearth furnace (OHF) route. The OHF route accounted for just 1.3% of production in 2010 and continues to decline due to poor economics compared to the other two routes, thus this route is excluded from the World Steel Association's LCI data (World Steel Association, 2011, p. 19). Countries that are known to still have operating OHF plants represent less than 3% of total UK steel imports (UK Steel, 2016, p. 10). Therefore, the OHF production route has also been excluded from the analysis conducted here.

Scrap steel is recycled via both the BOF and EAF routes, however, whilst scrap steel content in the BOF process is generally between 10 and 30% (World Steel Association, 2011, p. 72), the EAF process typically has much higher scrap content, up to 100% (World Steel Association, 2011, p. 11). This means that energy consumption per tonne of EAF steel is much lower than for BOF steel since the additional processing stage to reduce the iron ore is either not required (in the case of 100% scrap content) or is greatly reduced. Carbon emissions published for the EAF route are typically 60-85% lower than for the BOF route (Darby, 2014, p. 95 Table 3-32; Hammond & Jones, 2011 Material Profile: Steel)

Three sources of scenario uncertainty were initially identified through literature review, these were system boundary with respect to the treatment of recycling, level of data aggregation with respect to different production routes for steel and geographic representativeness, with respect to EU produced steel or steel from non-EU countries (rest of the world). Elicitations of uncertainty for steel were conducted with three experts (participants A, J and Q). All three proposed that allocation rules for co-products should also be included and suggested that physical allocation, economic allocation and no allocation be considered.

Participant Q advised that the system boundary choice would affect the choice of level of aggregation. The two choices for the system boundary were the recycled content approach (also known as the cut-off approach) and the system expansion (or closed loop) approach. Under the recycled content method the product stage carbon emissions (modules A1-3) only include the benefit of scrap input into the system and not the future recyclability. The system expansion method, as applied by the World Steel Association, includes the benefit of future recyclability into the embodied carbon factor for the product stage. In order to avoid double counting both the benefit of recycled content and the benefit of recycling, a net scrap value is calculated, whereby the amount of scrap input to the material is subtracted from the amount of recycled steel at the end of life. Under the recycled content method, the high scrap content of EAF steel contributes to the lower carbon factor compared to that of BOF steel. However, the use of the net scrap value in the system expansion method negates this difference, resulting in the two production routes having carbon factors much closer to the industry average. For this reason, in the scenarios where system expansion is selected, only the industry average of both production routes is subsequently modelled as has been depicted in the decision tree below.



[3 x 1 x 2 x 3] + [3 x 1 x 1 x 1] = 21 Scenarios

Figure 6-2: Decision tree representing the methodological choices and assumptions that give rise to scenario uncertainty in embodied carbon factors for structural steel

The results of the expert elicitation of scenario uncertainties for steel shown in the decision tree in Figure 6-2 lead to a total of 21 possible scenarios for which carbon factors were sought. Since the different scenarios relate to the product stages of the life-cycle, it was necessary to identify carbon factors for production of steel sections and sheet (module A1) and transportation to the fabricator or secondary manufacturer in the UK (A2). The emissions from fabrication (A3), transport to site (A4), construction (A5) and demolition and disposal (C1-4) are the same for all scenarios.

These carbon factors are then combined with the experts' assessments of statistical uncertainty presented in Table 6-4. The highest elicited values for the upper and lower bound have been used to represent the uncertainty range due to statistical uncertainty. This gives an upper bound of +30% and a lower bound of -15% and represents a conservative, or worst case, estimate of the effect of sources of statistical uncertainty.

Table 6-7 presents the carbon factors for the supply of un-fabricated structural sections (module A1) derived for each of the 21 scenarios along with details of which sources were used. The carbon factors for the remaining modules A2-4 and C1-4 are presented in Table 6-8.

Table 6-7: Carbon factors for production of structural steel for each of the 21 scenarios identified through expert elicitation of uncertainty and depicted in Figure 6-2.

Scenario	**Allocation to co-products**	**System Boundary (allocation of recycling)**	**Level of Aggregation**	**Production Route**	**Module A1 Carbon factor ($kgCO_2e/kg$)**	**Sources**	**Source Type**
Steel - 1	None	Recycled Content	EU	BOF*	2.652	1, 1	Industry
Steel - 2				EAF**	0.687	2, 1	Literature
Steel - 3				Avg.	1.886	3, 1	Literature
Steel - 4			Global	BOF	As EU		
Steel - 5				EAF	As EU		
Steel - 6				Avg.	2.331	4, 5	Comm. LCA
Steel - 7		System Expansion	Global	Avg.	1.230	6, 1	Literature
Steel - 8	Physical	Recycled Content	EU	BOF	2.440	1	EPD
Steel - 9				EAF	0.632	2	EPD
Steel - 10				Avg.	1.735	3	EPD
Steel - 11			Global	BOF	As EU		
Steel - 12				EAF	As EU		
Steel - 13				Avg.	2.030	4	Comm. LCA
Steel - 14		System Expansion	Global	Avg.	1.130	6	Govt.
Steel - 15	Economic	Recycled Content	EU	BOF	2.541	1, 1, 5	Literature
Steel - 16				EAF	0.653	2, 1, 5	Literature
Steel - 17				Avg.	1.807	3, 1, 5	Literature
Steel - 18			Global	BOF	As EU		
Steel - 19				EAF	As EU		
Steel - 20				Avg.	2.233	4	Comm. LCA
Steel - 21		System Expansion	Global	Avg.	1.177	6, 1, 5	Literature

Notes:

* BOF: Basic oxygen furnace route for steel production

** EAF: Electric arc furnace route for steel production

Sources:

1. Environmental Product Declaration - *Structural Steel Construction Products*. (Ruukki, 2014).
2. Environmental Product Declaration - EPD-CEL-20130219-IBD1-EN - *Structural Section Steel CELSA Group*. (Institut Bauen und Umwelt e.V., 2014a).
3. Environmental Product Declaration - EPD-BFS-20130094-IBG1-EN - *Structural Steel: Sections and Plates - BauforumStahl e.V.* (Institut Bauen und Umwelt e.V., 2013)
4. Table 3-32 in *Investigation of the Relative Impacts on Global Warming of Embodied and Operational Carbon Emissions from Buildings*. (Darby, 2014, p. 95)
5. Table 3-8 in *Investigation of the Relative Impacts on Global Warming of Embodied and Operational Carbon Emissions from Buildings*. (Darby, 2014, p. 53)
6. European Life Cycle Database (ELCD). (European Commission Joint Research Centre, 2013)

The carbon factors used for the remaining modules are shown in Table 6-8.

Table 6-8: Carbon factors selected for transport to the fabricator (module A2), fabrication (A3), transport to site (A4) and end of life processing (C1-4) for structural steel.

Module	Carbon Factor ($kgCO2_e/kg$)	Source Type	Notes on assumptions
A2	EU: 0.042 Global: 0.107	Literature	These figures represent a weighted average of transport emissions for steel sourced from the EU and steel sourced globally. They are based on factors originally derived by Darby (2014, p. 82 Table 3-23) but using updated industry data for UK steel imports (UK Steel, 2016, p. 10) and the most recent UK emissions factors for road and sea transportation (Department for Environment, Food and Rural Affairs, 2015)
A3	0.450	Comm. LCA	This value was estimated by Darby (2014, p. 82 Table 3-29) using SimaPro (SimaPro, 2015) and the Ecoinvent database. It is high compared with others quoted in EPD. It was chosen because it is the highest scoring data source (in terms of data quality) specific to the UK. Other data sources with higher data quality scores were for fabrication in Europe (for example Ruukki, 2014)
A4	0.0146	Govt.	Based on the average transport distance for UK metals in 2015 (Department for Transport, 2016) and the average emissions per tonne/km of HGV freight in the UK (Department for Environment, Food and Rural Affairs, 2015).
C1-4	0.06	Literature	This value is taken from end of life emissions factors published by a UK industry body (Steel Construction Institute n.d.). The value is apparently based on an assessment of end of life emissions for steel deck and hence it is has been listed here as derived from literature rather than as an industry carbon factor. The source provides no justification or comment as to comparability of steel deck and structural steel.

The following sub-sections 6.2.2.1 to 6.2.2.4 provide detailed explanation of how the different carbon factors for each alternative scenario in Table 6-7 have been derived.

6.2.2.1 Allocation to Co-Products

The majority of published carbon factors for steel are derived from the LCI data produced by the World Steel Association (Darby, 2014; Hammond & Jones, 2011). The World Steel methodology uses a form of physical allocation for co-products known as system expansion (World Steel Association, 2011). Hereafter, this method is referred to as the World Steel approach to avoid confusion with the system expansion approach to recycling which is discussed in 6.2.2.2 below. Under the World Steel approach, co-products are assigned a burden equivalent to the product that they replace and the main product is given a credit of the same amount. For example, the slag from the blast furnace is used either as secondary cementitious material (SCM, a replacement for cement) or as fill. According to the World Steel Association data, an average of 300 kilograms of slag is produced per tonne of steel. Of this, 94% is recovered and of the recovered slag, 82% is used as SMC and 17% as fill with one percent or less used in fertilizer (World Steel Association, 2011, p. 21 Table 5). The percentage used as SCM is assumed to replace clinker production (clinker is the main constituent of cement) at a ratio of 0.9 tonnes per tonne of cement (World Steel Association, 2011 Appendix 9). The slag used as fill is assumed to directly replace aggregates. Whilst the data that world steel use for the emissions of clinker and aggregate are not reported, it is possible to illustrate the effect of this allocation approach using emissions factors provided by the UK Mineral Products Association (MPA). The estimated carbon 'burden' applied to the co-products is shown in table x

Table 6-9: Emissions allocated to blast furnace slag under the World Steel allocation approach

	Slag used as SMC (GGBS)	**Slag used as fill**
Quantity per tonne of steel	0.231 tonne (82% of recovered slag)[1]	0.051 (17% of recovered slag)[1]
Emissions factor of avoided product	822 kgCO2e/tonne[1, 2] (=0.9 x 921)	4 kgCO2e/tonne[2]
Emissions for slag produced per tonne of steel	190 kgCO2e	0.2 kgCO2e

1 World Steel Association **(2011, p. 21 Table 5)**
2 Mineral Products Association **(2016, p. 5)**
SMC = secondary cementitious material
GGBS = ground granulated blast-furnace slag

The effect of applying equivalent credits to the carbon factor for BOF steel for the avoided production of cement and fill is a reduction of nearly 10% as shown in table x

Table 6-10: Illustrative example of the World Steel approach to allocation of emissions

	Carbon Factor (kgCO2e/t)	**Percentage**
BOF steel (without allocation)	2269[1]	100%
Credit for avoided production of cement	-190	-8.37%
Credit for avoided production of fill	-0.2	-0.01%
Emissions allocated to steel	2079	91.62%

[1] Ecoinvent **(2013 in Darby, 2014, p. 92 Table 3-29)**
BOF = Basic oxygen furnace

Whilst the allocation effects of GGBS are the most significant, there are other co-products in addition to slag which arise from steel production via the BOF route. So the example data in Table 6-9 and Table 6-10 serve to illustrate the principles of the World Steel approach and do not fully reflect its effects for all co-products. However, this estimate is consistent with the data in the World Steel LCA Methodology Report which indicates the effect of the allocation approach to be a reduction in the carbon emissions allocated to steel of between 5% and 10% (World Steel Association, 2011, p. 41 Figure 15).

All EPD from steel manufacturers that were reviewed for this research follow the World Steel approach to allocation. For example, the EPD from Ruukki Steel states that ‘allocation of by-products is calculated as reducing environmental impacts in the production of hot-rolled steel by 5-10%, and an average of 8%’ (2014, p. 7). In other words, the credits applied to steel for the avoided production of other materials such as SCM result in an average 8% reduction in the steel carbon factor.

Using this average value from the Ruukki Steel EPD (2014, p. 7), which is supported by the World Steel data (World Steel Association, 2011, p. 41 Figure 15), carbon factors which include a benefit based on the World Steel allocation approach have been increased to reflect a ‘no allocation’ scenario using the following equation:

$$Cf_{na} = \frac{Cf_{pa}}{0.92}$$ Equation 5.1

Conversion to ‘no allocation’ (derived from Ruukki, 2014, p. 7)

Where:

Cf_{na} is the estimated carbon factor without allocation

Cf_{pa} is a published carbon factor which is based on physical allocation

0.92 is the estimated proportion of total emissions from steel production which are allocated to steel using the World Steel methodology

Darby, presents carbon factors for steel without allocation and with economic allocation. He finds that with economic allocation, 95.8% of the carbon emissions from steel production are allocated to the steel itself (2014, p. 53). A similar result was found by Chen et al. (2010) but based on economic data from France. Thus, using the result from Darby, the following equation has been used to convert carbon factors where no allocation was used to reflect an estimate of the equivalent value if economic allocation were applied to co-products.

$$Cf_{ea} = 0.958\, Cf_{na}$$ Equation 5.2

Conversion to economic allocation (derived from Darby, 2014, p. 53)

Where:

Cf_{ea} is the carbon factor economic allocation

0.958 is the estimated proportion of total emissions from steel production which are allocated to steel using economic allocation

For example, the carbon factor published in Ruukki is 2.44 $kgCO_2e/kg$ and is based on physical allocation (2014, p. 8). This value is used directly for the scenario Steel – 8. For scenario Steel – 1, the same carbon factor has been converted using Equation 2.1 into a value for ‘no allocation’. Similarly, the carbon factor from CELSA Steel’s EPD (Institut Bauen und Umwelt e.V., 2014a) is used in its original form for scenario Steel – 9 but has been converted to ‘no allocation’ for Steel – 2.

6.2.2.2 Treatment of Recycling

The recycled content method is sometimes known as the cut-off approach (Jones, 2009) because a clear division is made between each life cycle and the burden for primary production of material is allocated entirely to the first use. Subsequent recycling is allocated to the second use in that the scrap material is assumed to have no environmental impacts except those arising from the re-melting process. System expansion brings forward the benefits of future recycling and credits these to the current life cycle. Thus, steel and other metals with high recovery and recycling rates at the end of life appear to have lower emissions when this method is used. In order to avoid double counting the benefits of recycling at both the beginning and the end of the life cycle, a burden must be applied to any recycled steel input to the manufacturing process. Appendix 10 of the World Steel LCA Methodology Report explains this procedure in detail and states:

> Where a material is recycled at end of life the product system is credited with an avoided burden based on the reduced requirement for virgin material production in the next life cycle. Equally, any recycled content adds the same burden to the product system in order to share the burden with the previous life cycle. (World Steel Association, 2011, p. 71)

The uncertainty assessment here includes scenarios for both the recycled content and the system expansion approach used by World Steel. The only source of publically available carbon factors for steel that was identified, which uses the system expansion method was the European Life Cycle Database (ELCD) (European Commission Joint Research Centre, 2013). The ELCD provides a carbon factor for steel based on global average production and this has been used directly for scenario Steel-14 (physical allocation) and has been modified using the equations in 6.2.2.1 for scenarios Steel-7 (no allocation) and Steel-21 (economic allocation). It would be possible to derive an equation for converting carbon factors based on recycled content to reflect the system expansion method, similar to the approach described above for converting data from one co-product allocation method to another. In this way additional carbon factors, to reflect the system expansion approach for EAF and BOF steel and EU production, could be derived. This was not done for three main reasons. Firstly, as has been described earlier in section 6.2.2 (see page 143), the net scrap approach applied to avoid double counting when using system expansion negates much of the difference between the carbon factors for the two production routes. Secondly, the system expansion method is not compliant with the standards for producing EPD (British Standards Institution, 2014a). The preference and support for the use of EPD data, which has been identified both in the literature and through the elicitation of data quality scores, suggests that the system expansion method is likely to become less common for construction products in future. Finally, in the literature on the system expansion approach, no figure could be found which explicitly states the effect that using this approach has on the carbon factor. Thus the derivation of a suitable conversion factor would be subject to greater uncertainty. For the purposes of this research, it was deemed that the inclusion of the ELCD data for average global production provides an indication of the effect that the system expansion approach has on the results when compared to the recycled content approach.

6.2.2.3 Steel Market

Production location has two important effects on the carbon factor of steel. Firstly, steel imports are likely to have travelled further and hence have higher transport emissions than UK produced steel. The second is the effect of different recycling rates in different parts of the world. Hammond and Jones (2011) argue that carbon factors for steel should be estimated at a level where the market can be considered to be self-sufficient to meet the demand for scrap. The average recycled content of UK produced steel is relatively low because most of the manufacturing facilities use the BOF production route. The UK therefore exports much of its scrap steel. Hammond and Jones estimate that the EU imports approximately the same amount of scrap as it exports and so they argue that it can be considered to be a self-sufficient market (Hammond & Jones, 2011 Annex B). Since the EU has a higher average recycled content for steel (59%) than the global average (39%), carbon factors for average EU steel are generally lower than for average global steel and this can be seen reflected in the values in Table 6-7 (for example comparing Steel-3 and Steel-6). However, since BOF production was found to have stable recycled content rates, the increased recycled content of EU steel is assumed to be due to a higher proportion of EAF produced steel in the EU than globally. The average recycled content of the two different production routes is assumed not to vary significantly between EU and global production and so the same carbon factor for module A1 for EAF and BOF steel is used for the EU and the global scenarios (see for example Steel-1 and Steel-2 compared to Steel-4 and Steel-5). The only difference between the carbon factors selected for EU EAF (or BOF) and global EAF (or BOF) steel therefore occurs in module A2, the transport from the steel producer to the fabricator in the UK. Emissions for this module are shown in Table 6-8.

6.2.2.4 Production Route

The data that are produced and promoted by steel industry bodies are based on the average of both the main production routes (British Construction Steelwork Association & Steel Construction Institute, 2014; Institut Bauen und Umwelt e.V., 2013; Steel Construction Institute n.d.). The rationale for adopting this approach has to do with the constrained market for scrap. The technical features of the two production routes mean that most recycled steel is processed via EAF since there is no upper limit on the scrap proportion. For BOF production on the other hand, the upper limit is around 30% (World Steel Association, 2011). Some steel products, particularly thin sheets, can only be viably produced using BOF steel because impurities introduced by the high scrap rates of EAF steel could cause weakness in the material (World Steel Association, 2011). The steel industry therefore argues that incentivising steel consumers to source steel with high recycled content, for example by reporting different carbon factors for EAF and BOF steel, could impede the most efficient use of steel scrap.

Nevertheless, a number of steel suppliers operating either EAF or BOF production have produced EPD for their products, which are necessarily not based on industry average data. These have been used here as sources of carbon factors for the specific production routes.

The carbon factors derived for the 21 scenarios for steel are presented graphically in Figure 6-3 along with the estimates of statistical uncertainty elicited during the individual interviews. The chart shows the combined effect of scenario and statistical uncertainties on the carbon factor for one kg of steel section.

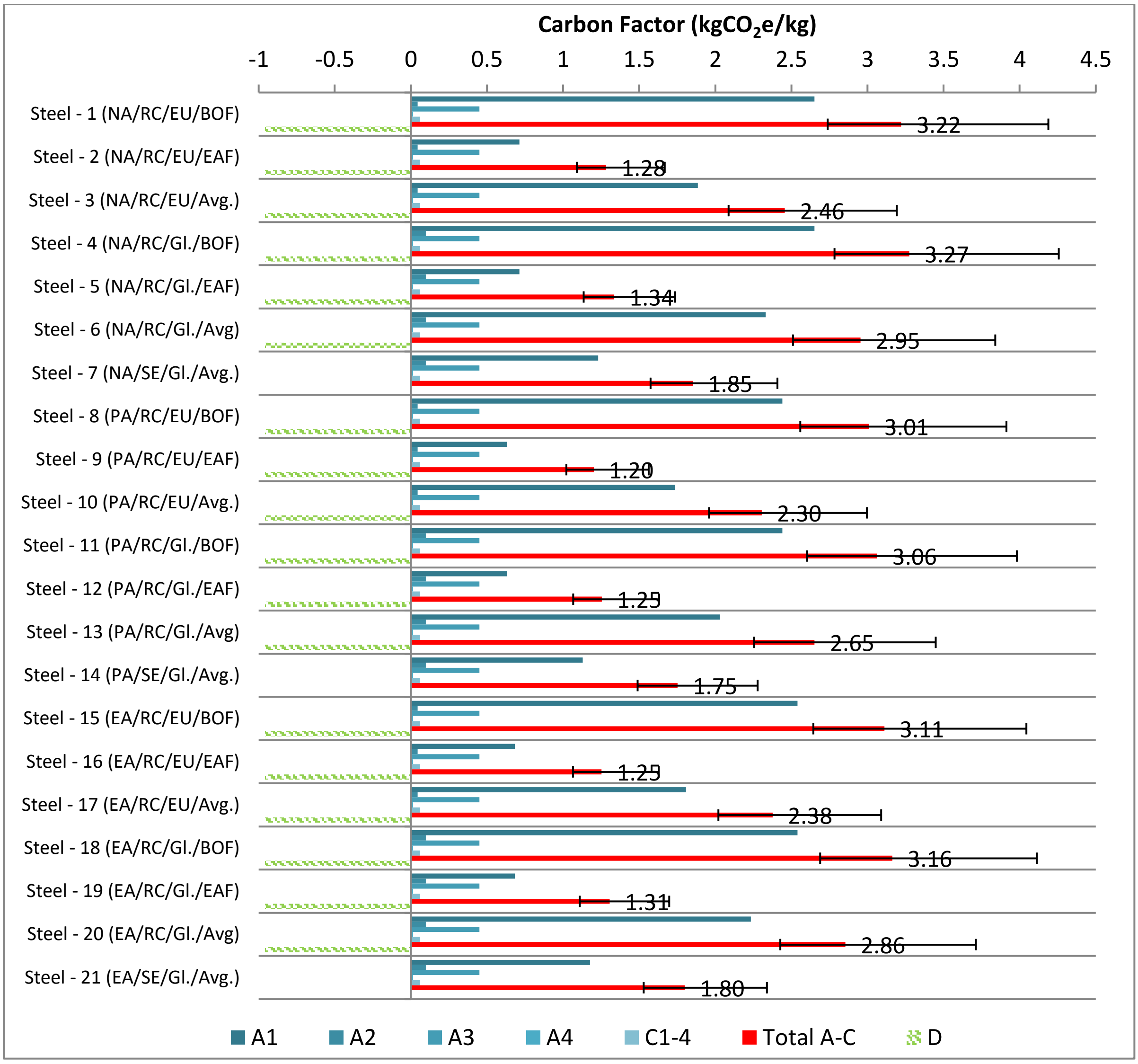


Figure 6-3: Uncertainty in the carbon factor of 1 kg of fabricated steel section for selected life cycle modules indicated based on elicited expert judgements

Notes:

The scenarios numbered Steel-1 – Steel-21 illustrate the effect of relevant sources of scenario uncertainty whilst the error bar applied to the total carbon factor for modules A-C illustrates the estimated effect of sources of statistical uncertainty.

The values shown for module D are indicative estimates included to illustrate how the recycled content and system expansion approaches differ in their treatment of these impacts. In reality further variation and uncertainty between the different scenarios using the recycled content method would be expected.

Scenario classifications:
NA = No Allocation
PA = Physical Allocation
EA = Economic Allocation
RC = Recycled Content method
SE = System Expansion method
EU = EU sourced steel
Gl. = Globally sourced steel
BOF = Basic Oxygen Furnace steel
EAF = Electric Arc Furnace steel
Avg. = Industry average of EAF and BOF production

Life cycle modules according to EN 15804:
A1 = Raw material supply
A2-3 = Transport of raw materials and production/manufacture
A4 = Transport of product to site
C1-4 = Demolition, waster transport and processing and final disposal
D = Benefits beyond the end of life (re-use, recovery, recycling etc.)
(British Standards Institution, 2014a)

The chart in Figure 6-3 shows that the effect of scenario uncertainties identified in this research is to cause the carbon factor of fabricated structural steel to vary between 1.2 and 3.27 kgCO$_2$e/kg. The effect of changing the method of allocation for co-products is much less significant than the effect of the other sources of scenario uncertainty. From Equation 2.1 and Equation 5.2 in section 6.2.2.1 above, the effect of the physical allocation method used by World Steel is to reduce the emissions for steel by around 8% and for economic allocation the reduction is around 4%. By contrast, comparing the results for Steel-6 and Steel-7 (or 13 and 14/20 and 21) show that changing the choice of system boundary with respect to recycling from the recycled content approach to the system expansion approach has the effect of reducing the carbon factor by around 37%. If carbon factors are assessed at the EU level, this has the effect of reducing the results compared to the global values by around 1.5% when considering BOF steel, 4.5% for EAF steel or 16.5% for average production. The reduction in the carbon factor for average production assessed at EU versus global level is greater than that for BOF and EAF because the average recycled content of EU produced steel is higher than the global average. In the assessment carried out here, the only difference for EAF and BOF steel scenarios when assessed globally compared to assessing at EU level is due to additional transport emissions (module A2) for globally sourced steel. The emissions factors for production (module A1) are the same for both global and EU BOF or EAF when only scenario uncertainty is considered. This is based on the assumption that globally, the average recycled content of BOF and EAF steel is similar to that of steel produced via each route in the EU. This is a reasonable assumption to make for BOF steel since there are technical limitations to the amount of recycled content that can be added. For EAF, the variation can be greater, however data comparing the average recycled content of EAF steel from different countries which could be used to model the difference that this makes to EU and global EAF were not found. There may be additional differences between global and EU emissions for EAF and BOF due to different average efficiencies and fuel mix in different parts of the world. In the method applied here, these issues have been treated as sources of statistical uncertainty and therefore their effect is not seen in the difference between the scenarios but is represented in the error bars in Figure 6-3 which are discussed in more detail below.

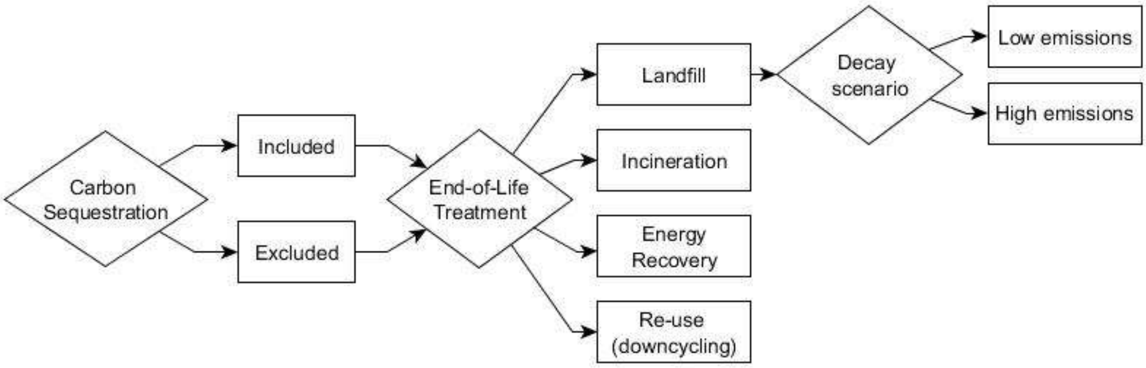
A comparison of the result for Steel-3 with Steel-1 and Steel-2 (or 6 with 4 and 5 etc.) shows that changing the data aggregation level from the average of both major production routes (EAF and BOF) to a specific production route can cause the carbon factor to increase by 9% (for BOF) or decrease by almost 40% (for EAF).

6.2.3 Timber

Timber is used in construction in a wide variety of applications. The applications considered in the material comparison case studies here include its use as a structural frame material (glulam) and as a material for the building envelope (composite insulated timber roof cassettes).

From the literature review, the sources of scenario uncertainty identified for timber were the methodological choice of whether to include the carbon sequestered during tree growth and the end of life processing options. For the end of life, three options of landfill, incineration and energy recovery were initially identified. For landfill, a further decision node was included to reflect different assumptions about the rate of decay of timber once sent to landfill. There is lack of consensus as to what proportion of the carbon stored in the timber is released back to the atmosphere as carbon dioxide (CO_2) and methane (CH_4) through decay. Analyses conducted in laboratory scale landfill simulations suggest that very little of the stored carbon is released in the 100 year assessment period (Wang et al., 2011; Doka, 2007), yet despite this data sources and embodied carbon assessments were found which assume that large proportions are released to the atmosphere as methane (Wood for Good, 2013b; Target Zero, 2011). An in depth assessment of the effects of this assumption, considering a range of different decay rates, is beyond the scope of this research. Moreover, UK Government policy has been to actively discourage timber being sent to landfill (Department for Environment, Food and Rural Affairs, 2011, 2013) and so these scenarios for the disposal of timber may become less relevant in future. For the purposes of evaluating and communicating the effect that the assumed rate of decay has as a source of uncertainty on embodied carbon factors, two alternative scenarios have been included. The rate of decay is measured in terms of the percentage of carbon which is released as either CO_2 or methane and this is known as the degradable organic carbon fraction (DOCf) (Hogg, Ballinger, & Oonk, 2011). The two scenarios included here are for a low decay rate (DOCf = 0.1%) and a high decay rate (DOCf = 38.5%) and these have been selected based on available data (Wood for Good, 2013b, p. 4).

Timber was assessed in two of the individual elicitations. The only amendment which was proposed by both experts was the inclusion of a fourth end of life scenario for the recycling of timber into manufactured boards (such as chipboard). This is reflected in the figure below and results in a total of 10 scenarios to be modelled.



[2 x 1 x 2] + [2 x 3] = 10 Scenarios

Figure 6-4: Decision tree depicting the main sources of scenario uncertainty for the embodied carbon of timber

Since the different scenarios relate to the product stages and the end-of-life stage, carbon factors were sought for modules A1-3, modules C1-4 and module D. The comparisons undertaken in the case studies involve a number of timber products:

- Glued laminated (glulam) timber – Case studies 7-1 and 7-2
- Oriented strand board (OSB) – Case study 7-2
- Birch plywood – Case study 7-2
- Timber I-Beams – Case Study 7-2
- Sawn softwood – Case studies 7-2

The carbon factors for modules A1-3 for timber are only affected by the first of the two decision nodes represented in Figure 6-4, that is, the inclusion or exclusion of sequestration. Therefore, for each of the five different types of timber, two carbon factors were derived for modules A1-3 and these are listed in Table 6-11.

These carbon factors are then combined with the experts' assessments of statistical uncertainty presented in Table 6-4. The highest elicited values for the upper and lower bound have been used to represent the uncertainty range due to statistical uncertainty. This gives an upper bound of +20% and a lower bound of -15% and represents a conservative, or worst case, estimate of the effect of sources of statistical uncertainty. The combined scenario and statistical uncertainty results are presented in Figure 6-5 on page 162.

Table 6-11: Carbon factors for the production (Modules A1-3 in EN 15804) of five types of timber construction product including sequestered carbon

Timber type		Carbon factor: raw material supply Modules A1-3 ($kgCO_2e/m^3$)			Data Source	Source Type*
		A1	**A2-3**	**Total A1-3**		
Glulam ω=12% ρ_ω=490 kg/m3 V_ω=0.983m^3 P_{CO2}=788kgCO$_2$	Seq.	-730.20	242.20	**-488.00**	Wood for Good Lifecycle Database – Glued Laminated Timber (Wood for Good, 2013a, p. 4)	Industry
	No Seq.	57.8	242.20	300.00		Literature
OSB ω=4.5% ρ_ω=617 kg/m3 V_ω=0.925m^3 P_{CO2}=1000.9 kgCO$_2$	Seq.	-943.1	183.10	**-760.00**	SWISS KRONO OSB-Platten EPD (Institut Bauen und Umwelt e.V., 2015a)	EPD
	No	57.8	183.10	240.90		Literature
Birch Plywood	Seq.	**-1090**	**266.00**	**-824.00**	Rüter and Diederichs (2012, p. 192)	Comm. LCA
	No Seq.	57.8	266.00	323.80		Literature
Sawn Softwood ω=15% ρ_ω=485 kg/m3 V_ω=1m^3 P_{CO2}=773kgCO$_2$	Seq.	-715.20	36.20	**-679.00**	Wood for Good Lifecycle Database – Kiln Dried Softwood (Wood for Good, 2013b, p. 5)	Industry
	No Seq.	57.8	36.20	94.00		Literature
Timber I-Beams **P_{CO2}=640kgCO$_2$**	Seq.	-582.5	221.60	**-418.71**	Masonite Timber I-Beam EPD (Norwegian EPD Foundation, 2015)	EPD
	No Seq.	57.8	221.60	279.40		Literature

Notes:

- Carbon factor values in bold typeface are taken directly from the source listed. Values in normal typeface are calculated using the method described in section 6.2.3.1.
- For Glulam, plywood and sawn softwood, the values for moisture content (ω) are taken from the sources listed in the table. The density (ρ_ω) is specific to the products considered in the case studies and is therefore taken from specifications provided by Sainsbury's. The volume (V_ω) of timber in the glulam, OSB and plywood is estimated from data in Rüter and Diederichs (2012 Tables 3.2.6.A, 3.2.10.A & 3.2.15.A). The sequestered CO_2 (P_{CO2}) is calculated using these values and Equation 5.3 (see section 6.2.3.1 below for details)
- For the timber I-beams, the value of sequestered CO_2 ($\boldsymbol{P_{CO2}}$) is provided in the EPD source listed.
- * Source type refers to the different sources of carbon factors assessed in the data quality matrix in section 5.3.2 of this chapter.

Table 6-12 shows the carbon factors for modules C1-4 and D which have been used to model different end of life scenarios for glulam timber. Whilst the values for end of life carbon factors differ for each of the other four types of timber, the relationships between the different scenarios follow the same pattern as those for glulam. The end of life carbon factors for the other four types of timber are presented in Appendix I: and the discussion here, whilst using glulam as an example, is relevant to all five types of timber.

Table 6-12: Carbon factors used to model scenario uncertainty for end of life (module C in EN 15804) and benefits beyond end of life (module D in EN 15804) for glulam timber

Timber Scenario	**Carbon Factors for Life Cycle Modules ($kgCO_2e/m^3$)**		**Sources**	**Source Type**
	C1-4	**D**		
Glulam - 1*	90.60	-0.22	(Wood Solutions Australia, 2015a, pp. 10 & 14; Steel Construction Institute)	Literature
Glulam - 2	934.00	-79.10	(Wood for Good, 2013a, p. 5)	Industry
Glulam - 3	846.00	0.00	(Wood for Good, 2013a, p. 5)	Industry
Glulam - 4	846.00	-593.00	(Wood for Good, 2013a, p. 5)	Industry
Glulam - 5	819.00	-8.41	(Wood for Good, 2013a, p. 5)	Industry
Glulam - 6*	90.60	-0.22	(Wood Solutions Australia, 2015a, pp. 10 & 14; Steel Construction Institute)	Literature
Glulam - 7	934.00	-79.10	(Wood for Good, 2013a, p. 5)	Industry
Glulam - 8	846.00	0.00	(Wood for Good, 2013a, p. 5)	Industry
Glulam - 9	846.00	-593.00	(Wood for Good, 2013a, p. 5)	Industry
Glulam - 10	31.00	-8.41	(British Standards Institution, 2014b, p. 5; Wood for Good, 2013a, p. 5)	Literature

Notes:
* The value of module C1-4 for Glulam 1 and Glulam 6 includes an estimate of emissions for demolition and waste transportation (C1 and C2) based on data for structural steel since these modules are not reported in the Wood Solutions EPD. The carbon factors used for the other scenarios are taken from EPDs which report modules C1-4 as an aggregated value. No source of timber specific data was identified with disaggregated values for modules C1 and C2.

The following sub-sections 6.2.3.1 and 6.2.3.2 provide detailed explanations of how the carbon factors in Table 6-11 and Table 6-12 have been derived.

6.2.3.1 *Credit for Sequestration*

The first methodological choice represented in Figure 6-4 is whether or not credit is given for the carbon sequestered in the timber during its growth cycle. This choice affects the carbon factor for the raw material supply, or life cycle module A1. The majority of carbon factors reviewed for this research do include credits for sequestered carbon, as this approach is compliant with EN 15804 (British Standards Institution, 2014a). Therefore, carbon factors for scenarios 1-5, where sequestration credits are included, were obtained directly from the data sources shown in Table 6-12.

In these data sources, the life cycle modules A1-3 were reported as an aggregated figure, with the exception of the values used for birch plywood. Estimates of the disaggregated figures for modules A1 and A2-3 were made in order that the A1 emissions could be adjusted to represent scenarios where sequestered carbon is not credited. The module A1 emissions include both the credit (negative value) for sequestered carbon in the timber and the burden (positive value) of forestry activities associated with the management and felling of trees. The sequestered carbon has been calculated using Equation 5.3.

$$P_{CO_2} = \frac{44}{12} \times 0.5 \times \frac{\rho_\omega \times V_\omega}{1 + \frac{\omega}{100}} \qquad \text{Equation 5.3}$$

Biogenic or sequestered carbon in timber (British Standards Institution, 2014b, p. 5 Equation 1)

Where:

- 44 is the molecular mass of carbon dioxide (CO_2) and 12 is the atomic mass of carbon (C)
- 0.5 is the assumed carbon fraction of the timber
- P_{CO2} is the carbon dioxide sequestered in the timber or timber product
- ω is the moisture content of the wood as a percentage
- ρ_ω is the density of the wood at the specified moisture content (kg/m^3)
- V_ω is the volume of wood (or the wood proportion of the product) at the specified moisture content (m^3)

(British Standards Institution, 2014b, p. 5)

The emissions from forestry activities are estimated to be 57.8 kgCO$_2$e per 1 m^3 of sawn timber (Wood Solutions Australia, 2015a, p. 12) and so this figure has been added to the values of sequestered carbon to give the total carbon emissions for the supply of the raw material (module A1) for each timber product. Emissions values listed in Table 6-11 for modules A2-3 (where these were not explicitly detailed in the EPD) were then estimated by subtracting the calculated carbon factor for A1 from the published aggregated carbon factor for modules A1-3.

6.2.3.2 End of Life Treatment

The end of life treatment of timber was a further source of scenario uncertainty identified during the elicitations. This impacts on the carbon factors for waste transport and processing (C2-3), final disposal (C4) and benefits beyond end of life (D). Since the choices modelled in the decision tree in Figure 6-4 relate to the treatment of waste after demolition, the carbon emissions for demolition activities (module C1) are assumed to be unaffected by these uncertainties.

The published carbon factors for different timber products often include multiple scenarios for the end of life treatment of timber. For example, Rüter and Diederichs (2012) model both energy recovery and recycling into wood chips for use in chip board. The UK *Wood for Good Life Cycle Database* (Wood for Good, 2013a) presents data for recycling, energy recovery and landfill with high decay rates assumed. The Australian timber industry EPDs present scenarios for recycling, energy recovery and two landfill scenarios, one based on high rates of decay and one based on low rates of decay (Wood Solutions Australia, 2015a). No single source includes all of the scenarios identified here through expert elicitation. Where more than one source of carbon data was available, the ranking based on data quality scores given in Table 6-3 has been applied to determine which source to use.

The end of life carbon factors identified in Table 6-12 have been combined with the carbon factors for the product stage for glulam shown in Table 6-11 and these values are plotted graphically in Figure 6-5 below along with the estimates of statistical uncertainty elicited during the individual interviews. The chart shows the combined effect of scenario and statistical uncertainties on the carbon factor for one cubic meter of glulam.

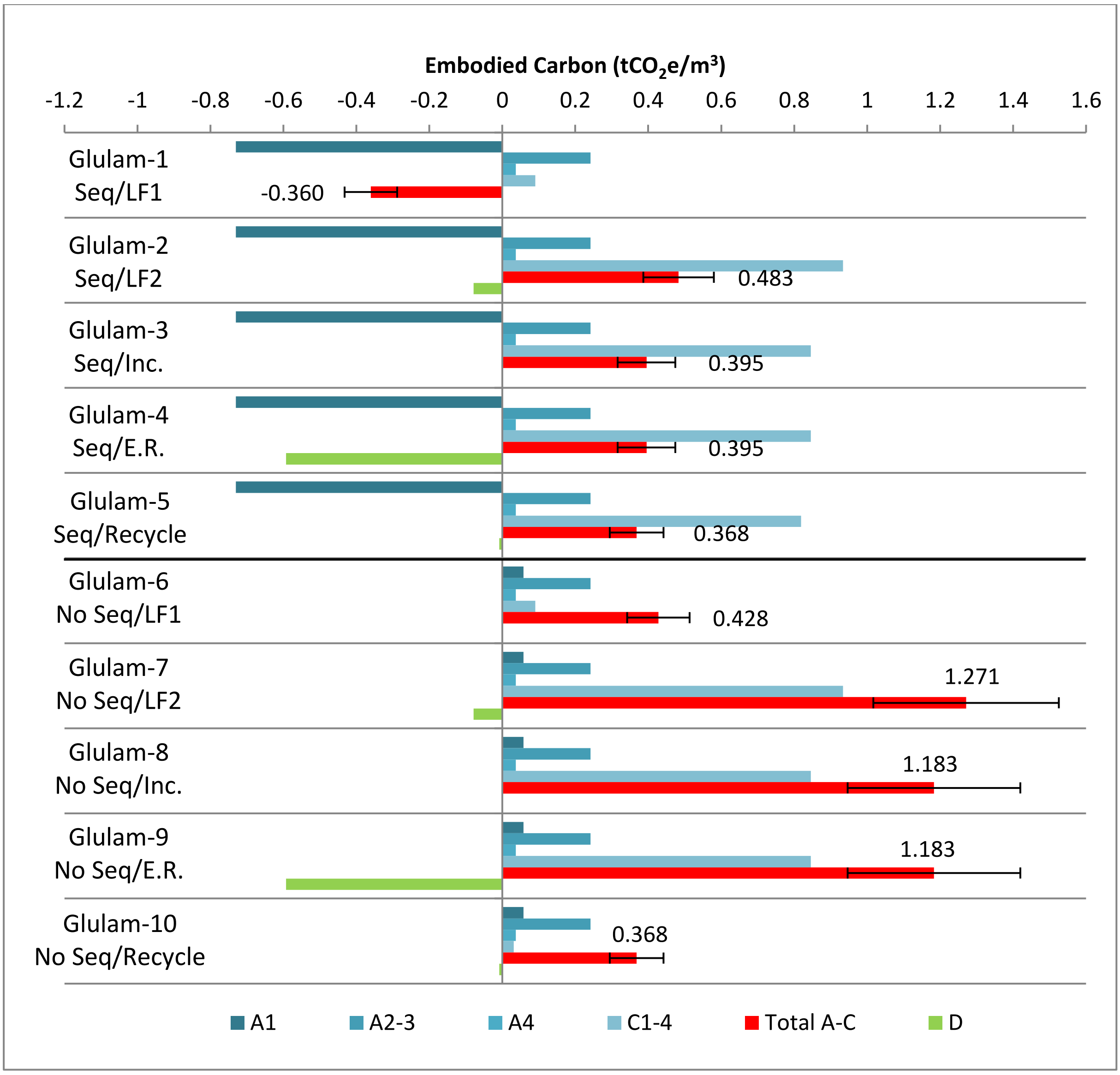


Figure 6-5: Uncertainty in the carbon factor of glulam timber for selected life cycle modules indicated based on elicited expert judgements

Notes:

The scenarios numbered Glulam-1 – Glulam-10 illustrate the effect of relevant sources of scenario uncertainty whilst the error bar applied to the total carbon factor for modules A-C illustrates the estimated effect of sources of statistical uncertainty.

Scenario classifications:
Seq. = Credit included for sequestration (scenarios 1-5)
No Seq = No credit included for sequestration (scenarios 6-10)
LF1 = Low emission landfill scenario for end-of-life
LF2 = High emission landfill scenario for end-of-life
Inc. = Incineration scenario for end-of-life
E.R. = Energy recovery scenario for end-of-life
Re-use = Re-use scenario for end-of-life

Life cycle modules according to EN 15804:
A1 = Raw material supply
A2-3 = Transport of raw materials and production/manufacture
A4 = Transport of product to site
C1-4 = Demolition, waster transport and processing and final disposal
D = Benefits beyond the end of life (re-use, recovery, recycling etc.)
(British Standards Institution, 2014a)

It is evident from Figure 6-5 that the greatest variation is caused by the choice of whether to include a credit for sequestration and the assumptions about landfill decay for the end of life treatment which are both sources of scenario uncertainty. By comparing scenarios with the same end of life option, it can be seen that for the incineration (Glulam-3), energy recovery (glulam-4) and landfill with high decay rates (Glulam-2) scenarios, the inclusion of credits for sequestered carbon reduces the total carbon factor for modules A-C (excluding those modules not within the scope) by 60-65%. For the landfill1 (Glulam-1) scenario, which assumes a low rate of decay of timber in landfill, including sequestration leads to a negative total carbon factor since the sequestered carbon is assumed to remain stored in the timber rather than being released to the atmosphere.

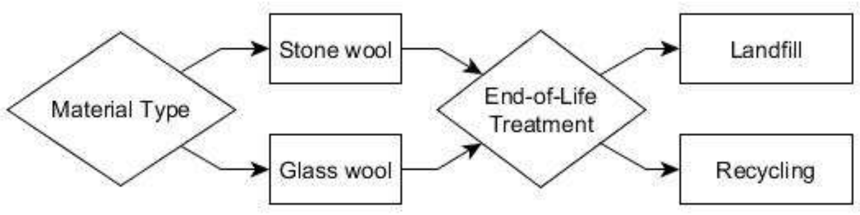
The scenarios where the timber is recycled (Glulam-5 and Glulam-10) represent the exception to this trend. Here the inclusion of sequestration makes no difference to the carbon factor for modules A-C. This occurs because the EPD methodology defined in EN 15804 requires that any sequestered biogenic carbon that is passed on to a second product life cycle must be included as a burden in the waste processing module C3. The purpose for this is to allow the second product to claim credit for this sequestered carbon as an input. If an equivalent burden in the waste processing module of the first product were not applied, this would effectively result in double counting of the sequestered carbon. The requirement to avoid double counting is a well-established principle of both LCA and product carbon footprinting (Ridoutt et al., 2016). However, in this case, it leads to somewhat counter intuitive results which appear to indicate that if the glulam is to be recycled, the total embodied carbon is unaffected by whether or not credit is given for sequestration. Furthermore, when comparing the emissions for different life cycle stages, the result for the Glulam-3 and Glulam-5 scenarios, there is little difference between the carbon factor for end of life emissions (modules C1-4) for recycling the glulam and for incinerating it. At first glance, this suggests that these two scenarios are comparable in terms of their climate change impact. Further consideration of what these numbers represent reveals that this cannot be the case. In the incineration scenario, the 0.788 tCO_2e of biogenic carbon are released directly to the atmosphere, primarily as gaseous CO_2. In the recycle scenario, this carbon remains in the timber and is not emitted to the atmosphere until the end of life of the subsequent product life cycle (or possibly later, depending on how that product is processed at end of life). To represent this stored biogenic carbon as an emission with global warming potential is not only confusing and misleading to those using the data but can also be viewed as scientifically inaccurate. This issue is further discussed in Chapter 8 (section 8.2.6.2).

6.2.4 Mineral Wool Insulation

Mineral wool can be manufactured from glass or stone and since glass wool typically contains a high proportion of recycled material, this has an impact on the embodied carbon. At early design stages, whether glass or stone wool is used would not necessarily be known and so this choice was included as a source of scenario uncertainty. This can be seen as an example of the level of data aggregation, similar to the choice between EAF, BOF and industry average data already explained for steel in section 6.2.2. However, the inclusion of an option for industry average mineral wool (using average emissions for both glass and stone wool) was not possible since an industry average figure was not found. Suitably detailed data on the market share of these two products in order to estimate such a value were also unavailable. The data that was identified is based on mass (Ecofys, Fraunhofer Institute for Systems and Innovation Research, & Oeko-Institut, 2012, p. 2) and indicates that roughly equal quantities of each are produced and sold. However, since stone wool is typically denser than glass wool for the same thermal performance, these statistics do not present a clear picture of market share in terms of the function.

In the UK, the end of life treatment for most mineral wool insulation arising from demolition currently is landfill (Dunster, 2007), however recycling is possible for both glass and stone wool and so this has been included as an option. During the expert elicitations conducted for mineral wool, it was highlighted that the recycled content of glass wool fluctuates depending on the availability of suitable glass cullet (scrap glass), however for the assessment carried out here, this was deemed to be a source of statistical uncertainty rather than scenario uncertainty since recycled content varies continuously between maximum and minimum limits rather than discretely.

Another source of uncertainty that was identified and explored was the allocation of emissions to secondary materials used for the production of stone wool. Both blast furnace and basic oxygen furnace slag (from iron and steel production) are used in the production of stone wool and typically these make up 20-30% of the raw material (Dunster, 2007, p. 6). It has been shown that the allocation method used has a significant impact on the embodied carbon factor of slags (e.g. Crossin, 2015; Darby, 2014; Chen et al., 2010: and see section 6.2.2.1) and so it is anticipated that this would also affect the embodied carbon of stone wool. However, the data reviewed provided insufficient detail to identify the contribution of slags to the carbon factors given. Moreover, none of the data sources reviewed made clear what allocation method had been used for the secondary materials such as slags (e.g. BRE, 2016a). It was therefore not possible to model this source of uncertainty in the scenario analysis. However, in their LCA of stone wool, Schmidt et al. find that ‘the major contribution to all environmental impact categories comes from the final production process and is almost exclusively related to the energy consumption.' And they go on to conclude that 'the acquisition of raw materials [is] of minor importance' (2004, p. 59). Therefore, the effect of different allocation methods for slags, which would only affect a small proportion of the emissions for supply of raw materials, is expected to be insignificant.



2 x 2 = 4 Scenarios

Figure 6-6: Decision tree depicting the main sources of scenario uncertainty for the embodied carbon of mineral wool insulation

The final decision tree diagram for mineral wool is shown in Figure 6-6 and leads to four different scenarios to be modelled. The carbon factors used to model these scenarios in the case studies are listed in Table 6-13.

Table 6-13: Carbon factors for product stage (modules A1-4 in EN15804) and end of life (modules C2-4 in EN15804) used to model the scenario uncertainties identified for mineral wool with a thermal conductivity of 0.034-0.035 $W.m^{-1}K^{-1}$

	Material type	**End of life treatment**	**Carbon Factor (kgCO2e/m^3)**				**Source**
			A1-3	A4	C2	C3-4	
Mineral Wool-1	Stone wool (45 kg/m3)	Landfill	53.80	0.605	0.285	0.202	EPD[1]
Mineral Wool-2	Stone wool (45 kg/m3)	Recycle	53.80	0.605	0.285	0.022	EPD[1] Govt. data[2]
Mineral Wool-3	Glass wool (25 kg/m3)	Landfill	25.80	0.364	0.179	0.115	EPD[3]
Mineral Wool-4	Glass wool (25 kg/m3)	Recycle	25.80	0.364	0.179	0.04	EPD[3] Govt. data[2]

1 Environmental Product Declaration - Rock Mineral Wool Insulation 33 - 45 Kg/Cu.m - Knauf. **(BRE, 2016a)**
2 DEFRA Carbon Factors. (Department for Environment, Food and Rural Affairs, 2015)
3 Environmental Product Declaration - Glass Mineral Wool Insulation with ECOSE Technology (0.034 – 0.035 W/mK) - Knauf. **(BRE, 2016b)**

6.2.4.1 Mineral Wool Type

A number of EPDs are available for both stone and glass wool insulation. These vary by the thermal conductivity[6] of the material and the intended application of the insulation, which affects its density and whether it has the form of slabs or a roll or is in a fibrous form for blowing into cavities, (ECO Platform, 2014). In most cases, the type of mineral wool to which the data apply is explicit, however examples exist where this is not the case and the type must be inferred from other details such as statements about the recycled content or the density (for example see Institut Bauen und Umwelt e.V., 2016 where high recycled content and low density suggest the data are for glass wool). For this research, the data selected were based on the specified requirement for the case study materials which determined the necessary thermal conductivity and application. In selecting carbon data for stone and glass wool, care was taken to ensure the same thermal conductivity values for both materials so that the insulating performance of each would be the same for a given thickness.

6.2.4.2 End of Life Treatment

All the mineral wool EPDs that were reviewed for this research assumed that the insulation is sent to landfill after demolition. Whilst take-back schemes for recycling mineral wool used in some internal fit-out applications exist, the same is not true for demolition waste because of concerns about impurities being introduced (Dunster, 2007). The data used here to model the recycling scenario are generic data for the recycling of unspecified insulation material (Department for Environment, Food and Rural Affairs, 2015). However, since mineral wool represents almost 60% of the European insulation market (Schmidt et al., 2004, p. 54), these data are expected to be fairly representative. The contribution of the end of life emissions for both the land fill and recycling scenarios can be seen from Table 6-13 to be of the order of 1% or less of the product stage emissions. Neither the EPDs reviewed, nor the carbon factors used for recycling included any data for the benefits beyond end of life (module D). For landfill these would be nil, since mineral wool is inert and would not contribute to production of landfill gas. For recycling, there is a small benefit and Schmidt et al. estimate the maximum potential energy saving from recycling of stone wool to be 3.2% of the energy consumption for primary production and so, in lieu of more accurate data, this figure has been used to provide an estimate of the carbon emissions credit for recycling in module D for both materials.

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[6] Thermal conductivity (λ) is a measure of how much thermal energy is transmitted through one linear meter of material for a given temperature gradient of one degree kelvin and it has units of watts per meter kelvin ($Wm^{-1}K^{-1}$). It is an intensive material property i.e., a property that is independent of the quantity of material. The lower the value of λ, the greater the material's resistance to heat transfer for a given thickness.

The carbon factors for the four scenarios are plotted graphically in Figure 6-7 below along with the estimates of statistical uncertainty elicited during the individual interviews. Since only one of the expert participants provided an estimate of statistical uncertainty (see Table 6-4) these values have been used here. The chart shows the combined effect of scenario and statistical uncertainties on the carbon factor for one cubic meter mineral wool insulation.

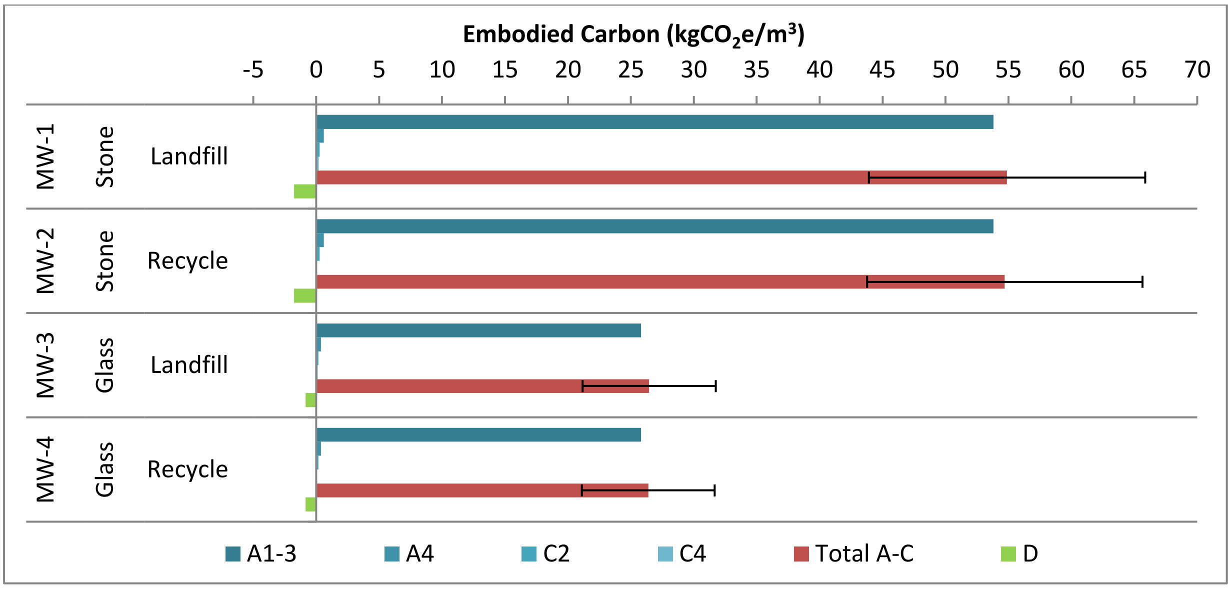


Figure 6-7: Uncertainty in the carbon factor of mineral wool for selected life cycle modules indicated, based on elicited expert judgements

Notes:
The scenarios numbered MW-1 to MW-4 illustrate the effect of relevant sources of scenario uncertainty whilst the error bar applied to the total carbon factor for modules A-C illustrates the estimated effect of sources of statistical uncertainty.

Scenario classifications:
Stone = stone wool insulation (sometimes called rock wool)
Glass = glass wool insulation (sometimes called fibreglass)

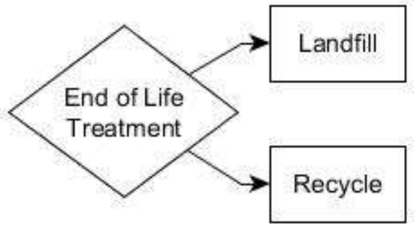
Life cycle modules according to EN 15804 (British Standards Institution, 2014a):
A1 = Raw material supply
A2-3 = Transport of raw materials and production/manufacture
A4 = Transport of product to site
C1-4 = Demolition, waste transport and processing and final disposal
D = Benefits beyond the end of life (re-use, recovery, recycling etc.)

The results in Figure 6-7 show that the product stage contributes around 98% to the total embodied carbon factor of both stone and glass wool. For this reason, the choice of material is the most important of the two sources of scenario uncertainty identified here, with emissions from glass wool around half those of stone wool for the same thermal conductivity. The choice of material has been included here as an example of the level of data aggregation, (although it has not been possible to derive an aggregated value for the average of both materials) and as such is an epistemic or reducible source of uncertainty (see the uncertainty matrix in Figure 5-1 on page 116). Therefore, the effects of scenario uncertainty for this material can be greatly reduced if the type of mineral wool is known. The statistical uncertainty, which has been estimated here to be +/-20% would remain and would then be the most important type of uncertainty for this material.

6.2.5 Polyurethane (PU) Insulation

For polyurethane insulation, only the end of life treatment was identified as a scenario uncertainty from the literature. The expert elicitations conducted raised two further issues which were considered but not included in the final diagram or scenario assessments. The first was the potential for different steps in the production of PU to be located in different parts of the world. PU is a plastic foam and hence its raw material comes from polymerisation of oil refinery products. The location of the oil feedstock, the refinery and the subsequent polymerisation and insulation manufacture may all occur in different locations. A full analysis of the plastic supply chain and transportation distances in order to determine how this uncertainty would affect the embodied carbon factor for PU was beyond the scope of this research. Moreover, the transport impacts of polyether polyol, the raw material for rigid polyurethane foam, are estimated to make up just 2% of the embodied energy of the material (Franklin Associates, 2011 Table 11-1) and it is reasonable to assume that the transport accounts for a similarly small proportion of embodied carbon. Therefore, uncertainty associated with transport distances is likely to have only minimal impact.

The second issue raised was the wide variety of densities of PU that are produced. The density of PU insulation varies as a range from around 30-50 kg/m^3 (European Isocyanate Producers Association, 1998, p. 9). However, the density will have a direct influence on the material's thermal conductivity (λ – see footnote 6 on page 166) as an insulant. In the material comparison case studies assessed in this research the required thermal performance was known and this determined the density of PU required. Therefore, density was not included as a source of uncertainty in this assessment.



2 Scenarios

Figure 6-8: Decision tree depicting the main sources of scenario uncertainty for the embodied carbon of polyurethane insulation

The carbon factors derived to represent these two scenarios are presented in Table 6-14.

Table 6-14: Carbon factors for product stage (modules A1-4 in EN15804), end of life (modules C2-4) and benefits beyond end of life (module D) used to model the scenario uncertainties identified for Polyurethane insulation with thermal conductivity of 0.035 W.m^{-1}K^{-1}

Scenario	End of life	Carbon Factor (kgCO$_2$e/kg)					
		A1-3[1]	**A4**[1]	**C2**[1]	**C3**[1]	**C4**	**D**[1]
PU-1	Energy Recovery	3.026	0.085	0.016	0.030	2.257[1]	-1.081
PU-2	Landfill	3.026	0.085	0.016	0.000	0.002[2]	0.000

1 EPD – PU Thermal Insulation Boards **(Institut Bauen und Umwelt e.V., 2015b)**
2 DEFRA Carbon Factors. **(Department for Environment, Food and Rural Affairs, 2015)**
PU = Polyurethane

The carbon factors for the product and construction life cycle stages were obtained from EPD data. The EPD assumed energy recovery would be used to process the insulant at the end of life and so this data has also been used directly for the first scenario. No EPD data for PU were found which included landfill as an end of life treatment option and therefore this scenario was modelled using government data for generic insulation sent to landfill.

The combined effects of scenario and statistical uncertainty as determined through the elicitations conducted here are shown in figure 6-9.

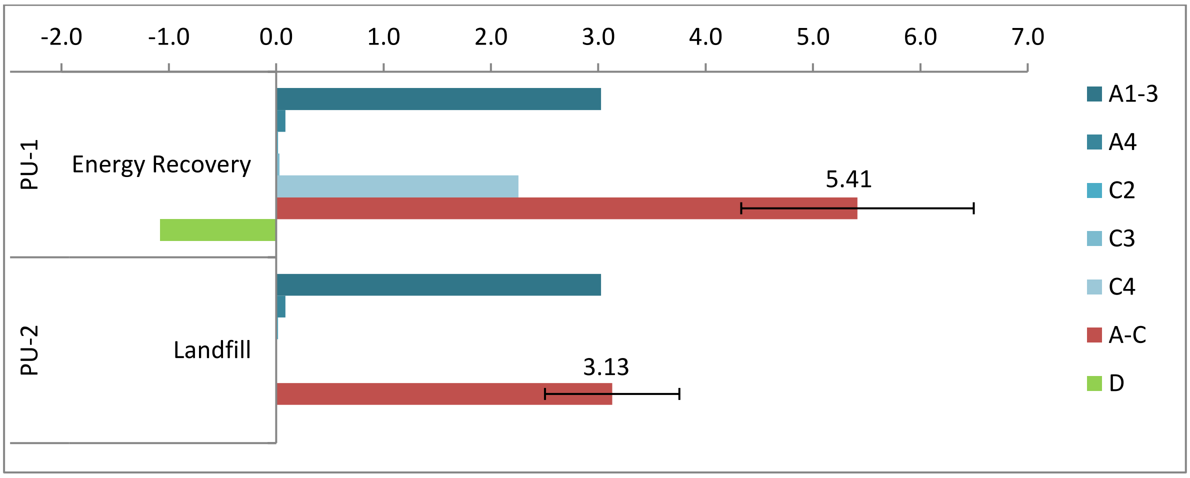


Figure 6-9: Uncertainty in the carbon factor of polyurethane for selected life cycle modules indicated, based on elicited expert judgements

Notes:
The scenarios numbered PU-1 to MPU-2 illustrate the effect of relevant sources of scenario uncertainty whilst the error bar applied to the total carbon factor for modules A-C illustrates the estimated effect of sources of statistical uncertainty.
Life cycle modules according to EN 15804 (British Standards Institution, 2014a):
A1-3 = Raw material supply, transportation and production/manufacture
A4 = Transport of product to site
C1-4 = Demolition, waste transport and processing and final disposal
D = Benefits beyond the end of life (re-use, recovery, recycling etc.)

Changing the assumed end of life processing has the effect of reducing the carbon factor of the insulation by around 40% which is significantly more than the estimate of statistical uncertainty, which for insulants was +/-20%. On a cradle to grave basis, the energy recovery scenario has the higher carbon factor since emissions from combustion are included whilst the credits for the energy recovered are only reported in module D. The modularity principle of EN 15804 sets the boundary for the current life cycle in such a way that the credits for energy recovery are passed on to the energy recovery facility (British Standards Institution, 2014a). If the benefit of energy recovery were also included in the cradle to grave carbon factor for PU, this would effectively lead to double counting. Moreover, as can be seen from the chart above, even if the credit were included. the carbon factor would still be higher than that estimated here for landfill. This is due to the inert nature of the material, meaning it would degrade only very slowly and greenhouse gas emissions would be negligible. There are likely to be other undesirable consequences to sending the material to landfill and this serves to highlight how carbon emissions are not always a reliable proxy for other environmental impacts. A full LCA would be necessary to investigate these other impacts but this is beyond the scope of the current work.

6.2.6 Concrete

In UK supermarket construction, the main use of concrete is for structural foundations and floor slabs. Whilst aggregates typically account for around 70-90% of the mass of concrete, around 90% of the carbon emissions are due to cement manufacture. Standard cement, usually referred to as Portland cement or ordinary Portland cement (OPC), is produced by calcination of lime, a process that is very energy intensive and releases CO_2 as a by-product of the reaction. The cement industry is responsible for around 2% of global energy consumption (Kumar & Naik, 2010, p. 1) and some 5-7% of all CO_2 emissions (Van den Heede & De Belie, 2012, p. 431). A number of alternative materials with cementitious properties are available and can be used to replace a proportion of the OPC in a concrete mix. These are known as supplementary cementitious materials (SCM) and the two most commonly used are PFA and GGBS. PFA is produced from coal fired power stations whilst GGBS is a by-product of primary steel production. Both products have much lower carbon emissions per kilogram than OPC and hence their use is often cited as a way to reduce the embodied carbon of concrete (Darby, 2014). There are other cement replacements available such as limestone fines or silica fume, however these have not been considered here since they do not arise in the case studies and they are less commonly used in the UK than GGBS and PFA (Habert, 2013).

The assessment of scenario uncertainty was undertaken for each constituent of concrete (aggregates, cement, and SCMs) separately with a further assessment carried out for concrete from the point of mixing the constituents onwards. These assessments and results are presented in the following sections 6.2.6.1 to 6.2.6.4.

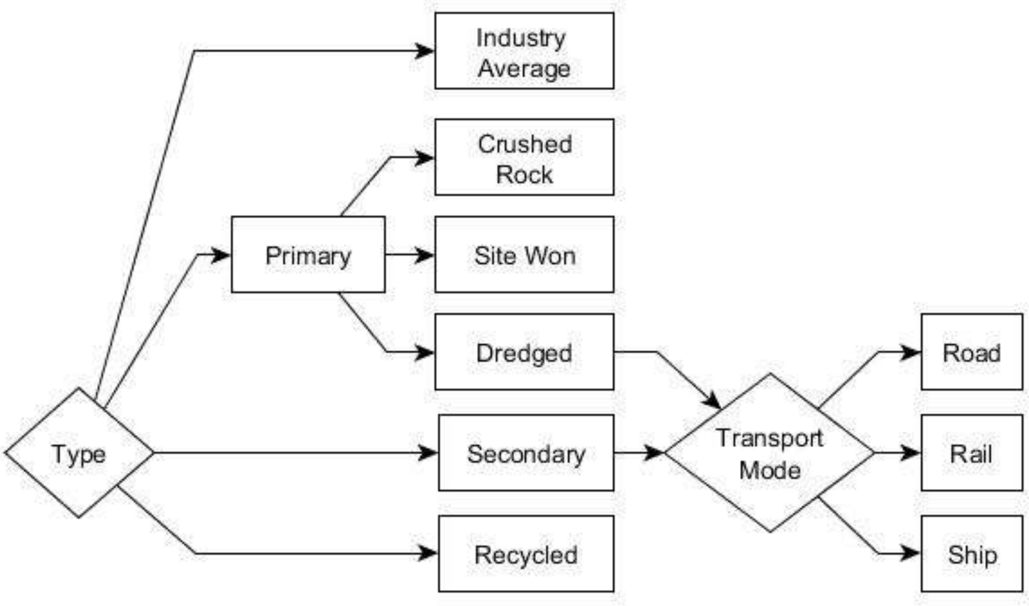
6.2.6.1 Aggregates

For the material comparison case studies considered here, aggregate is assessed solely as a constituent of concrete. In addition to their use in concrete, aggregates are used in construction as fill and to provide a stable base for hard surfaces such as roads and car parks. However, these applications are not considered in this assessment. In the initial review, the level of data aggregation was identified as an important source of scenario uncertainty. A number of different types of aggregates exist which are each sourced in different ways. The choice of whether to use industry average carbon data or data for a specific type of aggregate will affect the results of the embodied carbon of the concrete. In the first diagram produced for the uncertainty elicitation for aggregates, the options presented for different types of aggregate were either virgin or recycled. From the elicitations, a number of additional important distinctions were highlighted by the experts, in particular the distinction between secondary and recycled aggregates and the different types of virgin or primary aggregates that can be used. These are shown in the diagram below. All three experts discussed the important contribution of transport emissions are for the overall embodied carbon of aggregates due to the high density and the large volumes typically required for concrete. Whilst transport has been identified as a statistical uncertainty in the uncertainty matrix in Figure 5-1, the different types of aggregate identified during the elicitations are typically associated with particular transport scenarios. For example, site won primary aggregate and site processed recycled aggregate both have no transport emissions. On the other hand, quarries for crushed rock aggregates are often co-located with concrete works and so the only transport required is as ready mixed concrete, from the concrete works to the site. Secondary aggregates and plant processed recycled aggregates on the other hand typically undergo two journeys, firstly from the production plant to the concrete works and then on to the site in the form of ready mixed concrete. Thus since transport already forms part of the scenario uncertainty identified for aggregate, and since the transport emissions constitute a relatively large proportion of the total embodied carbon of aggregates, it was decided that the mode of transport should be included as a source of scenario uncertainty to be included in the assessment.

Two experts interviewed suggested that lightweight aggregates be explicitly included as an additional category. Lightweight aggregates can be natural or man-made, and both types have been shown to have higher embodied carbon than standard weight aggregates (Darby, 2014 Table 3-17). However, as one of the experts pointed out, lightweight aggregates are most commonly applied in specialist applications such as high-rise construction, where weight is an important consideration. Therefore they were not included in this assessment.

The diagram in

Figure 6-10 depicts the source of scenario uncertainty identified which led to a total of 16 scenarios to be modelled.



3 + [2 x 3] + 1 = 10 Scenarios

Figure 6-10: Decision tree depicting the main sources of scenario uncertainty for the embodied carbon of aggregates

The carbon factors derived for each of the scenarios are shown in Table 6-15. When applying the modularity principle of EN15804 to materials that are intermediate constituents of composites products as is the case here, there is some ambiguity as to which emissions should be assigned to each module. For this assessment, the modules have been defined with respect to the concrete rather than the individual constituents. Hence, the emissions associated with quarrying, crushing or other processes are assigned to module A1 since these relate to obtaining a raw material for concrete. Any transport of the aggregates is assigned to module A2, since this is occurs prior to the production of concrete, emissions from which are then assigned to module A3. This is a similar approach to that adopted for steel in section 6.2.2 above, where the modules have been defined with respect to the fabricated steel rather than the un-fabricated steel sections.

Table 6-15: Carbon factors for raw material extraction (module A1 in EN15804) and transport (module A2 in EN15804) used to model the scenario uncertainties identified for aggregates

Scenario	**Type of Aggregate**		**Transport Mode**	**Carbon factor (kgCO$_2$e/kg)**				**Source Type (A1/A2)**
				A1	**Source**	**A2**	**Source**	
Agg-1	Average			0.0040	1	0.0080	2	Industry/Industry
Agg-2	Primary	Crushed Rock	None	0.0028	3	0		Comm. LCA
Agg-3		Site Won	None	0.0004	4	0		Comm. LCA
Agg-4		Dredged	Road	0.0100	5	0.0109	7,8	Industry/Govt.
Agg-5		Dredged	Rail	0.0100	5	0.0122	8, 9	Industry/Lit.
Agg-6		Dredged	Ship	0.0100	5	0.0016	8, 9	Industry/Lit.
Agg-7	Secondary		Road	0		0.0109	7,8	Govt.
Agg-8			Rail	0		0.0122	8, 9	Literature
Agg-9			Ship	0		0.0016	8, 9	Literature
Agg-10	Recycled		None	0.0079	6	0		Industry

Notes:

1. Mineral Products Association (Mineral Products Association, 2016, p. 5)
2. Mineral Products Association (2017a, p. 7)
3. Darby (2014, p. 63)
4. Darby (2014 Table 3-16)
5. Aumônier et al. (2010, p. 9)
6. Mineral Products Association (2017b Table 3)
7. Department for Transport (2016)
8. Department for Environment, Food and Rural Affairs (2015)
9. Office of Road and Rail (2017 Tables 3.16 and 3.17)

6.2.6.1.1 Type of Aggregate

The carbon factors for raw material extraction (A1) for the different types of aggregates listed have been obtained directly from the sources indicated. At the time this research was carried out, no EPDs for aggregates were listed on either the Eco Platform (2014) or the Environdec (EPD International AB, n.d.) websites and further internet searches for relevant EPDs were unsuccessful. As has been discussed, the type of aggregate has an effect on the likely transportation requirements. For crushed rock, it has been assumed that there is no transport involved, since the literature suggests it is common for sources of this type of primary aggregate to be co-located with concrete works (Darby, 2014). Similarly, for site won and recycled aggregates, it has been assumed that the aggregate is processed and mixed into concrete on site with no transport required. These assumptions are based on what were deemed for this research to be the most likely situations arising. Alternative arrangements may occur, such as where recycled aggregates are brought in from another site or site won aggregates are taken away to a concrete works for batching and then brought back as ready mixed concrete. These are less likely due to the economic and logistical implications of additional haulage. The use of the modularity principle from EN 15804 means that the data presented in Table

6-15 could be manipulated in order to model such scenarios if required by combining emissions factors for A1 and A2 from two different scenarios.

6.2.6.1.2 Transport Mode

The emissions factors for the different modes of transport are taken from the most recently published data from the Department for Environment, Food and Rural Affairs (Defra) (2015) which provide carbon factors for a wide range of different types of road vehicle and cargo ship and just one factor for emissions from rail transport. For road transport, the carbon factor used represents the average carbon emissions for all heavy goods vehicles (HGVs) and the average load factor for all journeys. For transport by ship, the selected carbon factor was the average value for all bulk carriers. These emissions factors are given per tonne and kilometre ($kgCO_2e/t.km$) and so an estimate of the distance travelled is also required. In design stage assessments where specific transport distances may not be known, average transport statistics for different types of product may be used and this approach has been applied here. The average distance for road transport is taken from the most recently available Road Freight Statistics from the Department for Transport (2016) and applies to all quarried material. Average rail transport distances are not published in this format, however, the Office of Road and Rail publishes quarterly data for rail freight moved (in units of tonne kilometres) and freight lifted (tonnes) and so an estimate of the average distance that each tonne of freight is transported can be derived from the quotient of the two values (freight moved / freight lifted)[7]. Whilst the freight moved data are presented for seven different categories including construction materials, the freight lifted statistics are only provided for all freight and for coal. Therefore, the average distance calculated here is based on all freight other than coal. The data for the most recent four quarters were used to estimate an average transport distance for rail freight of 235 kilometres as shown in Table 6-16.

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[7] The Department for Transport Road Freight Statistics derive average road freight distance data in the same way (Department for Transport, 2016) The Department for Transport Road Freight Statistics derive average road freight distance data in the same way (Department for Transport, 2016)

Table 6-16: UK rail freight statistics used to estimate average journey distance for all freight other than coal (Office of Rail and Road, 2017 Tables 3.16 and 3.17)

Quarter	**Freight Lifted (million tonnes)**	**Freight Moved (million tonne kilometres)**		
	Other (a)	All freight (b)	Coal (c)	Other (d = b - c)
15-16 Q4	16	4,210	460	3,750
16-17 Q1	16.5	4,200	250	3,950
16-17 Q2	16.5	4,230	320	3,910
16-17 Q3	17.3	4,420	460	3,960
Total	**66.3**	**17,060**	**1490**	**15,570**
			Average Distance (d_{total} / a_{total}) =	**235 km**

According to the most recent data available, rail freight accounts for around 12% of all transport within the concrete supply chain and is associated with longer journeys (Mineral Products Association, 2014, p. 7). Therefore, transport distances by rail would be expected to be greater than those for road. Nevertheless, it is not clear how representative the value calculated in Table 6-16 is for aggregates since the data apply to all freight except coal.

For the scenarios where transport is by ship, no appropriate statistics were found by which to estimate average distances. For the purposes of this research, it was deemed likely that, similar to rail freight, ships would be used for longer journeys than road freight. In the absence of specific data, the same average distance for rail freight (235 km) has been used for ship freight as this illustrates the greater efficiency of shipping per kilometre. This efficiency improvement would be negated if the distance travelled were significantly greater. However a comparison of the transport emissions for Agg-8 and Agg-14 (rail and ship respectively) shows that the emissions for shipping freight are around 13% of those for rail for the same distance and so shipping is likely to emit less carbon than rail, even for distances up to around seven times greater or approximately 1600 km.

In the rail and ship scenarios it has been assumed that the aggregates can be brought directly to the concrete works or to the site batching plant via this mode of transport with no need for additional road journeys in between. This has been done to simplify the analysis and make a clear comparison possible between the three modes of transport.

The data from Table 6-15 are plotted graphically in Figure 6-11. The statistical uncertainty has not been included since this was assessed for concrete as a composite material rather than for the individual constituents. The figure therefore represents the effects of scenario uncertainty on the carbon factor for one kilogram of UK produced aggregate used in concrete.

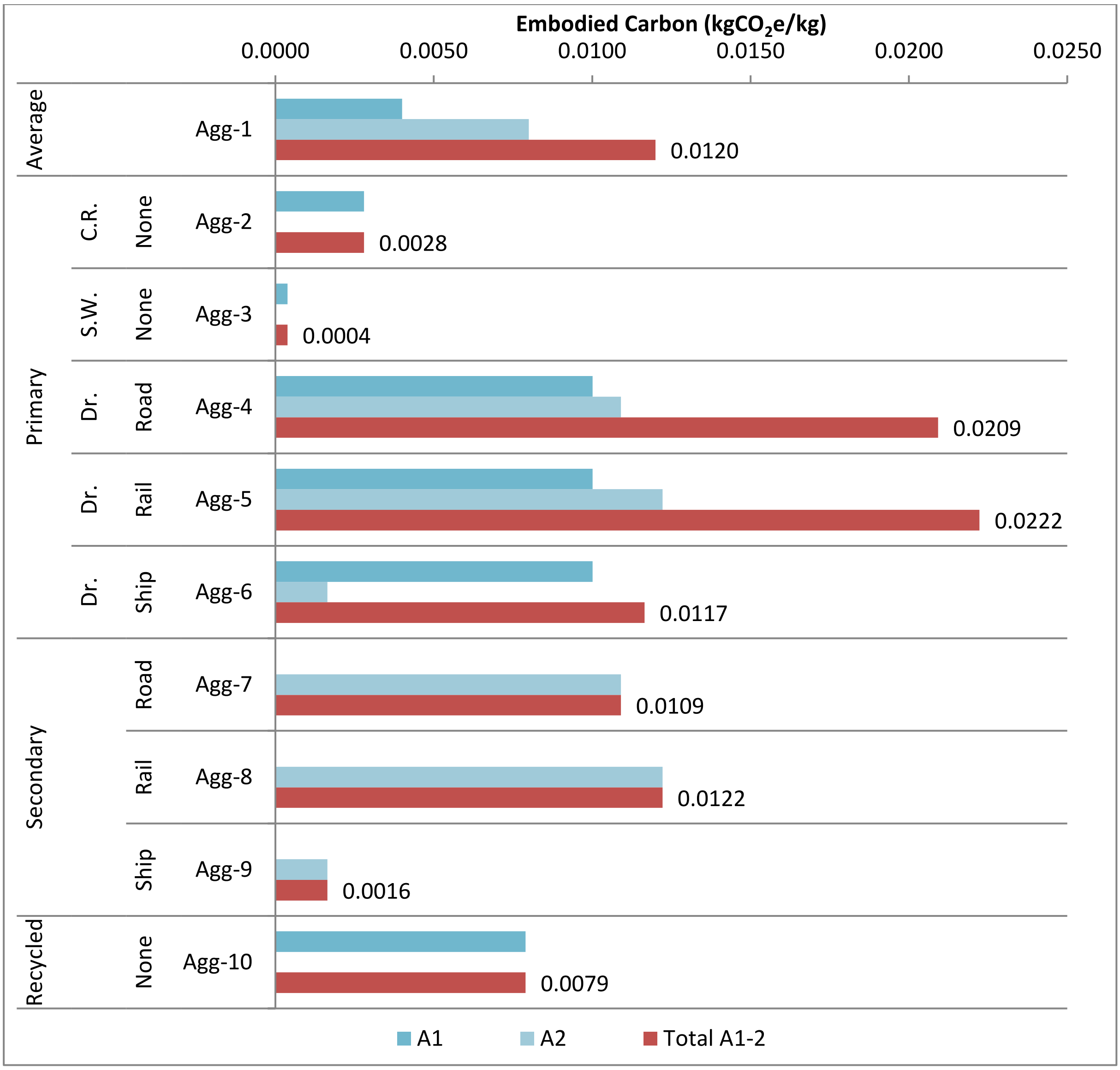


Figure 6-11: Uncertainty in the carbon factor of aggregates for selected life cycle modules indicated, based on elicited expert judgements

Notes:
The scenarios numbered Agg-1 to Agg-16 illustrate the effect of relevant sources of scenario uncertainty as indicated.

Scenario classifications:
Average refers to average emissions for all UK supplied aggregates
Primary/secondary/recycled refers to the type of aggregate and primary aggregates are further distinguished as:
C.R. = crushed rock (quarried)
Dr. = marine dredged
S.W. = site won
Road/Rail/Ship/None refers to the assumed mode of transport

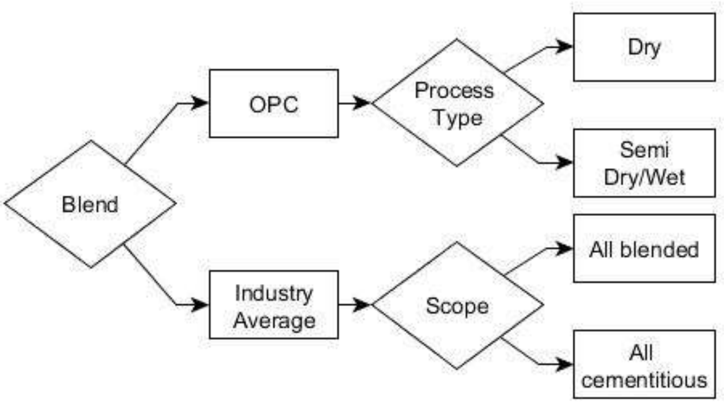
Life cycle modules according to EN 15804 (British Standards Institution, 2014a)
A1 = Raw material supply (in this case includes all processes required to produce the aggregate)
A2 = Transport of raw materials (includes all transport of the aggregate up to the location where the concrete is batched)

The results in Figure 6-11 show that the assumption made about the type of aggregate has the most significant effect on the embodied carbon factor since this can affect both the emissions for raw material acquisition (A1) and for transport (A2). The highest emissions are associated with marine dredged aggregates, which have a carbon factor that is 75-85% higher than the industry average if transported average distances by road or rail. Site won aggregates have the lowest carbon factor which is just 3% of that of the industry average. Transportation by rail is shown to marginally increase the total carbon factor compared to road transport for the average distances used here, for example Agg-5 is just over 6% higher than Agg-4. This suggests that whilst rail is much more efficient per kilometre travelled, the greater distances that are involved may negate the benefits. However, if long distances are unavoidable, rail is obviously preferable to road from a carbon perspective. Where transport is involved, the lowest transport emissions are for the scenarios where ship freight has been assumed. However, there are likely to be only very limited cases where this would be logistically and economically viable due to the required proximity to a waterway or coastline and suitable port facilities for loading and unloading.

6.2.6.2 Cement

Initial scenario uncertainties identified from the literature for cement related to the level of data aggregation and the end of life treatment. The level of aggregation considered is in relation to the blend of cement and the type of production process. Data are typically either aggregated for all UK supplied cement blends, which include proportions of cement replacements, or are given specifically for production of ordinary Portland cement (OPC). There are different production processes for OPC depending on the water content of the feedstock. The different processes have different energy requirements and hence the embodied carbon of the cement. In the UK, three processes are used and these are known as dry, semi-dry and semi-wet (British Geological Survey, 2014). It was not possible to derive separate carbon factors for the semi-dry and semi-wet processes and so in Figure 6-12 these are shown as a single alternative to the dry process.

All the experts queried whether including the different types of production process in the assessment was necessary since the purchaser would generally have very little influence over whether the cement that they buy has been produced using the dry, semi-dry or semi-wet process. For this research, the question of whether a source of uncertainty can be controlled or influenced was deemed to be secondary to the goal of identifying and communicating the effects of uncertainty on embodied carbon assessment results. Therefore, the type of process has been included in the sources of scenario uncertainty as shown in Figure 6-12. This is consistent with literature on uncertainty assessment as can be seen in the example of Walker et al.’s (2003) uncertainty matrix (see Figure 5-1 on page 116), where uncertainties that cannot be reduced (variability uncertainty) are explicitly included in the typology.



[1 x 2] + [1 x 2] = 4 Scenarios

Figure 6-12: Decision tree depicting the main sources of scenario uncertainty for the embodied carbon of cement

The carbon factors derived for production of cement for each of the scenarios are given in Table 6-17. As a constituent of concrete, cement is an intermediate rather than an end product and so only the production stages of the life cycle are assessed here, since the use phase and end of life are dealt with for concrete as a composite material. As with aggregates, the decision has been taken to define the life cycle modules with respect to the end product, concrete. Therefore, all processes associated with manufacture of cement are accounted for here under module A1, raw material extraction, treating cement as a raw material for concrete production.

Table 6-17: Carbon factors for raw material extraction (module A1 in EN15804) used to model the scenario uncertainties identified for cement production

Scenario	Scenario description		Carbon factor: A1 (kgCO$_2$e/kg)	Source	Source Type
Cement-1	100% OPC	Dry	0.921	1	Comm. LCA
Cement-2	100% OPC	Semi-Dry/Semi-Wet	1.105	1, 2	Literature
Cement-3	Average	Blended cements	0.846	3	EPD
Cement-4	Average	All cementitious material	0.787	4	Industry

Notes:

* Average emissions based on UK supplies of blended cements which include 100% OPC cements also known as CEM I and blends of OPC with PFA, GGBS and limestone fines which are designated as CEM II-IV.

** Average emissions based on UK supplies of blended cements and supplies of unblended PFA and GGBS

† OPC: Ordinary Portland cement

†† Dry, semi-dry and semi-wet refer to different cement production processes.

Sources:

1. Table 3-5 in *Investigation of the Relative Impacts on Global Warming of Embodied and Operational Carbon Emissions from Buildings*. (Darby, 2014, p. 49)
2. Table 3 in *Emission Reduction of Greenhouse Gases from the Cement Industry* (Hendriks et al., 1998, pp. 4–5)
3. MPA EPD (Institut Bauen und Umwelt e.V., 2014b)
4. MPA Factsheet 18 (Mineral Products Association, 2012)

6.2.6.2.1 Cement Blend

Whilst no EPDs for OPC was available at the time the research was undertaken, a review of various carbon factors for OPC conducted by Darby (2014) found values for UK produced OPC of 0.913 (Mineral Products Association, 2012) and 0.95 kgCO2e/kg (Hammond & Jones, 2011). Darby also derives a UK specific value for OPC using commercial LCA software (SimaPro and Ecoinvent), estimating the carbon factor to be 0.921 kgCO2e/kg. This value was used here since data from commercial LCA were assessed as having higher data quality than the sources of the other two factors listed (industry and literature derived data respectively).

The UK Mineral Products Association (MPA) has produced an EPD for UK cement based on the weighted average of all blended cements. Somewhat confusingly, the EPD is entitled *UK Average Portland Cement*. However, it is clear from the details provided in the accompanying report that the data are not for 100% OPC, as could be construed from the title, but represent blended cement with an average of 4% PFA, 3.2% limestone and 1.1% GGBS (Institut Bauen und Umwelt e.V., 2014b, pp. 2–3). Elsewhere the MPA (2012) also present a value for average UK cement which is based on the weighted average of all UK supplied cementitious materials. This figure includes unblended PFA, limestone and GGBS and is therefore lower than the value for blended cements given in the EPD.

6.2.6.2.2 Process Type

In the literature and data sources reviewed, no data could be found which differentiated between carbon emissions for the dry, semi-dry and semi-wet processes which account for 11.4 and 13.8% of UK production capacity respectively (British Geological Survey, 2014). Data presented by Hendriks et al. suggest that CO_2 emissions from wet production (not a current practice in the UK) are around 20% higher than for dry production (Hendriks et al., 1998 Table 3). The semi-dry and semi-wet processes are less energy intensive than the wet process (Hendriks et al., 1998) and so it is to be expected that they also produce less CO_2 emissions. However, in lieu of any data specific to these processes, it has been assumed that the carbon factor for OPC derived by Darby represents the dry process and this has been increased by 20% to give a conservative estimate of the emissions from semi-wet and semi-dry cement production.

The carbon factors selected to model the four scenarios identified in Figure 6-12 are plotted graphically in Figure 6-13.

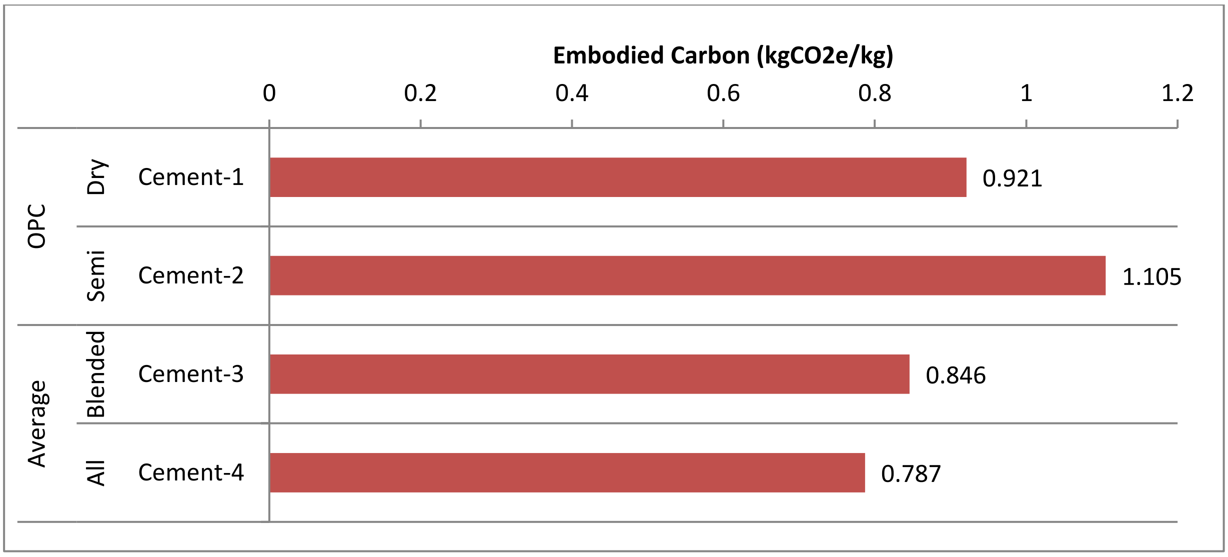


Figure 6-13: Uncertainty in the carbon factor of UK cement based on elicited expert judgements

Notes:
The scenarios numbered Cement-1 to Cement-4 illustrate the effect of relevant sources of scenario uncertainty as indicated. Data are for all processes required to produce cement. As a raw material for concrete, these emissions are accounted for in life cycle module A1 (raw material supply).

Scenario classifications:
OPC = Ordinary Portland Cement
Dry = dry OPC production
Semi = semi-dry or semi-wet OPC production
Average Blended = weighted average emissions based on UK supplies of blended cements which include 100% OPC cements and blends of OPC with PFA, GGBS and limestone fines
Average All = weighted average emissions based on UK supplies of blended cements and supplies of unblended PFA and GGBS

Assessing the carbon factor for cement as a weighted average of all UK “cement” rather than as dry OPC has the effect of reducing it by around 8% if only pre-blended cements are considered or 15% if all cementitious material is included. This is not quite as great a difference as that between the estimates for the semi-dry or semi-wet production process and the more common dry production. However since the 20% increase applied here (for semi-dry and semi-wet) is a conservative estimate, the effect of these two sources of uncertainty is shown to be of the same order of magnitude.

The industry average value based on all cementitious material (Cement-4) is 7% lower than that for average blended cements (Cement-3). Both of these values are produced by the MPA. The MPA advises that the lower value should be used when the specific cement blend is not known, for example at early design stage. It is not clear from the MPA guidance why the lower value should be used in preference to the higher value given in the EPD, nor is it clear in what situations the MPA deems the EPD value to be appropriate. This lack of guidance adds to the uncertainty associated with assessing the embodied carbon of cement and concrete.

The uncertainty assessment method developed and applied here makes explicit the fact that this difference is due to a methodological choice in the calculation and does not indicate that one type of cement will result in lower carbon emissions. Furthermore, methodological choices such as this have been defined as sources of scenario uncertainty using the uncertainty matrix. The separate treatment of scenario and statistical uncertainties proposed and demonstrated here ensures that these sources of scenario uncertainty are not hidden in an uncertainty range or probability distribution but are distinctly identified.

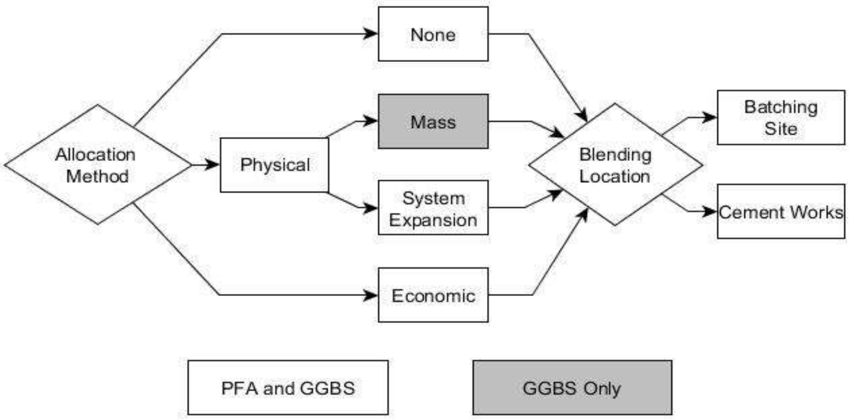
6.2.6.3 Supplementary Cementitious Materials (PFA And GGBS)

The cement replacements or SCMs included in this assessment are both co-products of other industrial processes. PFA is a co-product from coal fired electricity generation and GGBS is a co-product of the reduction of iron ore into pig iron in a blast furnace, an important preliminary stage in steel production via the BOF route. The main source of scenario uncertainty affecting these two materials is therefore the allocation method selected to determine what proportion of the emissions from these processes (coal fired power generation and blast furnace operation) to allocate to these two co-products. The three experts consulted agreed with this, with two suggesting that in addition to the initial proposal to include scenarios for no allocation and economic allocation, physical allocation also be included.

The types of physical allocation that have been assessed in previous studies include mass (Grist et al., 2015; Darby, 2014; Chen et al., 2010), volume (Darby, 2014) and system expansion (Crossin, 2015; World Steel Association, 2011), which is described in section 6.2.2.1. Allocation by volume or mass is not applicable in the case of PFA, a co-product of electricity which has no mass or volume. For GGBS, Darby demonstrates that allocation by volume leads to around 65% of the emissions from steel production being allocated to the slag (approximately 50% to GGBS and 15% to fill) and just 35% to the steel (Darby, 2014, p. 53 Table 3-8). Given that the primary purpose of production is clearly steel and not slag (blast furnaces would not be operated to produce slag if there were no demand for steel), this allocation method is not considered appropriate.

Economic allocation methods are usually based on an assessment of the market value of the co-products (Darby, 2014; Chen et al., 2010). However Habert (2013) has also proposed using the European emissions trading scheme (EU-ETS) as a basis for allocating an equal share of the carbon saved through the use of SCMs to each industry (steel and cement or coal power and cement). However his paper does not present results in terms of an absolute carbon factor for each material but rather as a percentage of the carbon factor for cement. This approach leads to carbon factors for GGBS and PFA which are around 55 % and 45 % of the carbon factor for OPC respectively (Habert, 2013, p. 122 Figure 2). This is comparable to other economic allocation approaches which results in carbon factors of around 40% of the value of OPC for both PFA and GGBS (see values in Table 6-18). Given the lack of absolute figures and the similarity to the economic scenarios already included, Habert's approach has not been included as a separate scenario here.

The allocation methods included in the assessment are thus, economic (for PFA and GGBS), mass (GGBS only), system expansion (PFA and GGBS) and no allocation (PFA and GGBS).



PFA: 3 x 2 = 6 Scenarios GGBS: 4 x 2 = 8 Scenarios

Figure 6-14: Decision tree depicting the main sources of scenario uncertainty for the embodied carbon of cement replacements pulverised fly ash (PFA) and ground granulated blast-furnace slag (GGBS)

The carbon factors for both SCMs which were selected for each of the scenarios are presented in Table 6-18.

Table 6-18: Carbon factors for raw material extraction (module A1 in EN15804) and transport up to the concrete batching location (module A2) used to model the scenario uncertainties identified for production of supplementary cementitious materials

Scenario	**Allocation method**	**Blending Location**	**Carbon Factor (kgCO2e/kg)**			**Source Type ***
			A1	Source	A2 [6, 7]	
GGBS-1	None	Batching site	71	1	15.5	Commercial LCA
GGBS-2		Cement Works	71	1	31.0	Commercial LCA
GGBS-3	Mass	Batching site	1544	1	15.5	Literature
GGBS-4		Cement Works	1544	1	31.0	Literature
GGBS-5	System	Batching site	829	2, 3	15.5	Literature
GGBS-6	Expansion	Cement Works	829	2, 3	31.0	Literature
GGBS-7	Economic	Batching site	365	1	15.5	Literature
GGBS-8		Cement Works	365	1	31.0	Literature
PFA-1	None	Batching site	0	4	15.5	Commercial LCA
PFA-2		Cement Works	0	4	31.0	Commercial LCA
PFA-3	Mass	Batching site	N/A			
PFA-4		Cement Works	N/A			
PFA-5	Economic	Batching site	553	2, 5	15.5	Literature
PFA-6		Cement Works	553	2, 5	31.0	Literature
PFA-7	System	Batching site	375	3	15.5	Literature
PFA-8	Expansion	Cement Works	375	3	31.0	Literature

Notes:

GGBS = Ground granulated blast-furnace slag; PFA = Pulverised fly ash

* Source type refers to carbon factors for A1. A2 carbon factors are all from sources 6 & 7 which are both government data sets.

Sources:

1. Darby (2014 Table 3-8)
2. Darby (2014 Table 3-5)
3. World Steel Association (2011 Appendix 9)
4. Darby (2014 Table 3-10)
5. Habert (2013, p. 116)
6. Department for Environment, Food and Rural Affairs (2015)
7. Department for Transport (2016)

6.2.6.3.1 Allocation Method

The values for carbon factors for raw material acquisition (module A1) are all taken either directly or are adapted from those derived by Darby (2014) using Ecoinvent . This is consistent with the data quality ranking for carbon factors established in section 6.1. Alternative values for the carbon factors without allocation were considered from the Mineral Product Association (MPA) (2012), however these would have a lower data quality score since they are taken from an industry source rather than commercial LCA. The MPA values are very close to those provided by Darby with both estimating the carbon factor of GGBS to be round 7-8% of the carbon factor of OPC and that of PFA to be less than 1% of that of OPC. Since blast furnace slag must undergo some additional processing in order to produce GGBS, the emissions from this processing are attributed to the GGBS which results in higher carbon factor than that for PFA even when none of the emissions from the primary process (blast furnace or coal combustion) are allocated to the SCM.

For the system expansion method of allocation, no published data was found. The cement and concrete industry do not typically promote or apply this approach, which is unsurprising given that it leads to significantly higher carbon factors for both GGBS and PFA. The carbon factors in Table 6-18 for GGBS-3 and PFA-3 have been calculated as shown in the table on the basis that the binding property (or κ-value) of 1 kilogram of PFA and GGBS are equivalent to 0.6 and 0.9 kilograms of OPC respectively (Habert, 2013, p. 116; British Standards Institution, 2013).

6.2.6.3.2 Blending Location

The blending location affects the number of journeys required between the production of the SCM and the concrete batching. For the scenario where blending occurs at the batching location, the SCM is assumed to make a single journey from the production facility to either a concrete works or the site depending on whether the concrete is ready mixed or site batched (see section 6.2.6.4.1 below for an explanation of batching location). If blending takes place at the cement works, then two journeys are needed, one from the production location to the cement works and a subsequent journey (as blended cement) to the batching location (either concrete works or site). The MPA estimate the transport of PFA to the concrete works to produce emissions of 7 kgCO2e/kg (2012, p. 5). As a carbon factor from an industry source, the data quality ranking developed in section 6.1 would suggest that this should be preferred to the government data that is included in Table 6-18. However, it is not clear from the accompanying text whether this MPA estimate is based on blending taking place at the cement works or the concrete works, nor is any detail given of the assumed distance or an equivalent estimate of transport emissions for GGBS. Therefore, it was necessary to use the government data to model the two alternative blending location scenarios.

The carbon factors for each scenario are plotted graphically in Figure 6-15. As statistical uncertainties were assessed for concrete rather than for each constituent of concrete, the figure represents the effect of the scenario uncertainty identified through expert elicitation.

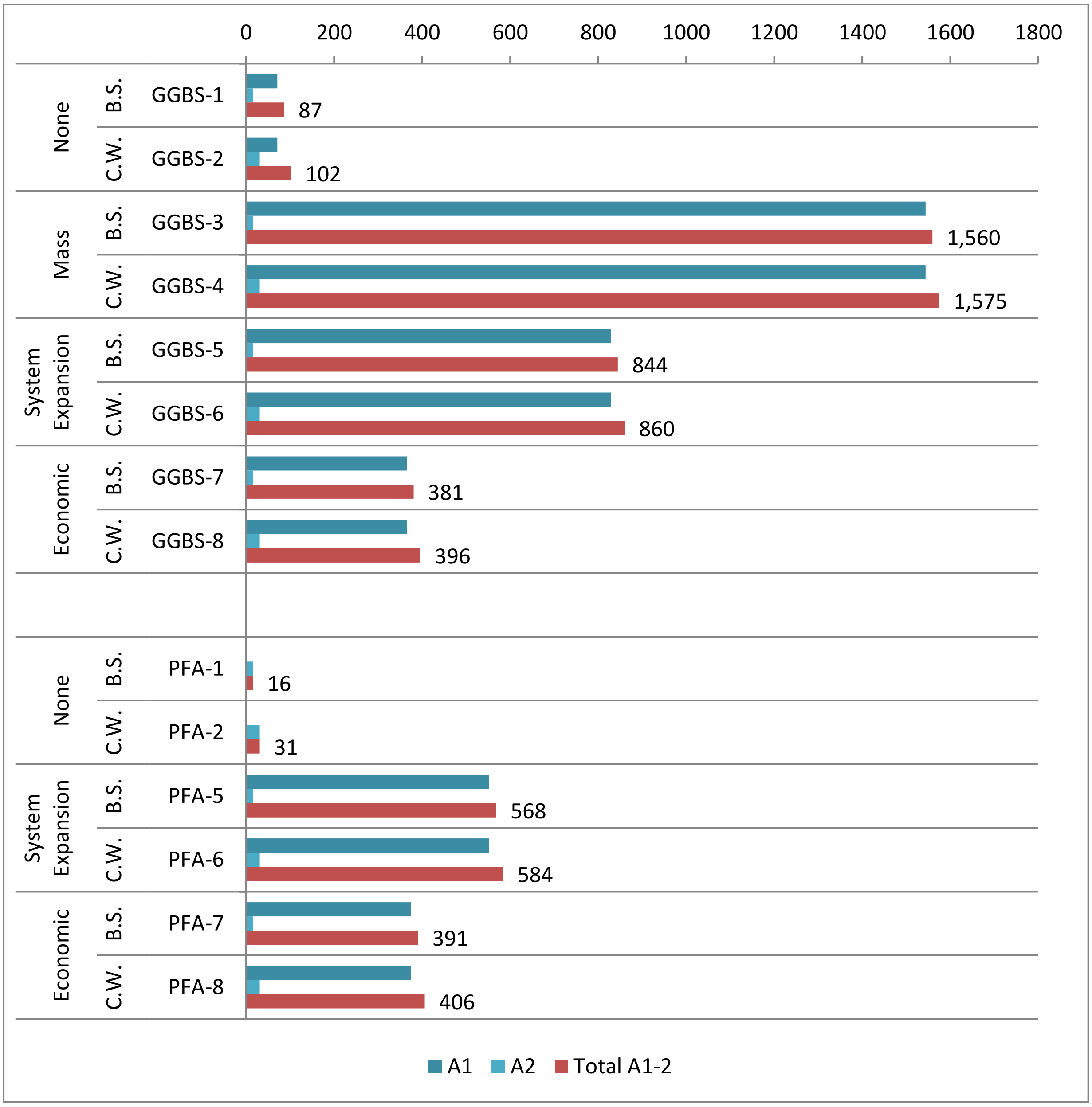


Figure 6-15: Uncertainty in the carbon factor for raw material acquisition (module A1 in EN 15804) of ground granulated blast-furnace slag (GGBS) and pulverised fly ash (PFA) based on elicited expert judgements.

Notes:
GGBS = Ground granulated blast-furnace slag; PFA = Pulverised fly ash
The scenarios numbered GGBS 1-8 and PFA 1-8 illustrate the effect of relevant sources of scenario uncertainty as indicated. Scenarios PFA-3 and PFA-4 are omitted since mass allocation is not applicable.
Data are for all processes required to produce GGBS or PFA (A1) and transport to the concrete batching location (A2).

Scenario classifications:
None, Mass, System Expansion and Economic refer to the co-product allocation method
B.S. = Blending with OPC takes place at the concrete batching site (either concrete works or construction site)
C.W. = Blending with OPC takes place at the cement works

Consistent with the previous studies cited above, the allocation method is shown to have a very significant effect on the embodied carbon of the two SCMs considered here. For GGBS, the use of mass allocation results in a carbon factor 23 times greater than if no allocation is applied and, if used, means that GGBS has a higher embodied carbon than the OPC it is replacing. The system expansion method, which is the approach used and promoted by the steel industry, results in carbon factor for GGBS almost 12 times greater than without allocation. For PFA, which is shown here as having zero emissions, a numerical comparison gives

Not allocating any of the emissions from the primary process implies that the SCM is a waste rather than a co-product. However, it has been argued by Habert (2013) and Van Den Heede and De Belie (2012) that under the EU *Directive on Waste*, GGBS and PFA can no longer be defined as wastes, since 'further use of the substance or object is certain' (European Union, 2008).

In order to justify not including any form of allocation for SCMs, the MPA refers to the guidance on allocation in EN 15804. Co-products with an economic value of less than 1% of the total revenue may be neglected for the purposes of allocation (British Standards Institution, 2014a). Whilst this is generally accepted to be true for PFA, the situation is less clear for GGBS. The MPA's claim that in the UK 'the revenue from blast-furnace slag relative to the total revenue (iron + slag) was only of this order and that allocation was therefore not necessary' (2012, p. 8) is not supported by the analysis conducted by Darby (2014) for the UK or that of Chen (2010) who analysed prices based on French data. Prices for metals and minerals fluctuate and Darby acknowledges that estimating the price of GGBS in the UK is difficult because it is 'largely controlled by the single supplier' (2014, p. 51). His analysis is therefore based on an approximation of the price as a percentage of the price of bulk cement rather than on actual price data for GGBS. Whilst the MPA do not reveal the source of their pricing information, as the industry body for cement and concrete in the UK, their members hold this information and so the MPA assessment may be more accurate than that of Darby.

The question of which allocation method to apply continues to be highly contentious (Habert, 2013) and is particularly problematic for SCMs since the different methods lead to significantly different outcomes. The analysis conducted here shows that carbon factors from different sources, all claiming to follow EN 15804 guidance, adopt different allocation methods for the same materials. The guidance in EN 15804, which is intended to 'enable comparability of the results of assessments' (European Committee for Standardisation (CEN) - Technical Committee 350, 2016), fails to give the clarity needed to resolve this issue. It is therefore particularly important that the effects of different allocation choices as a source of scenario uncertainty are understood. The method proposed here allows for this and this is further analysed and discussed in the case study of alternative concrete specifications in section 7.3.

The results in Figure 6-15 show that uncertainty relating to the blending location has a much less significant effect on the carbon factor than the allocation method. Proportionally, the greatest impact of this is seen when comparing PFA-1 and PFA-2 since for these scenarios, the only emissions are due to transport and so blending at the cement works has the effect of doubling the carbon factor versus blending at the batching site. However, for the other scenarios, where transport emissions (module A2) are a much smaller contributor to the overall carbon factor, the effect of assuming a different blending location is greatly reduced. For example, comparing PFA-7 and PFA-8, the difference is just a 4% increase if blending takes place at the cement works.

6.2.6.4 Concrete

The final diagram for concrete presents the scenario uncertainties which relate to the mixed concrete (rather than for the constituent materials which have been assessed and discussed in sections 6.2.6.1 to 6.2.6.3).

In UK supermarket construction, the main use of concrete is for structural foundations and floor slabs. Whilst aggregates typically account for around 70-90% of the mass of concrete, around 90% of the carbon emissions are due to cement manufacture (see Table 6-19 below). Standard cement, usually referred to as Portland cement or ordinary Portland cement (OPC), is produced by calcination of lime, a process that is very energy intensive and releases CO_2 as a by-product of the reaction. The cement industry is responsible for around 2% of global energy consumption (Kumar & Naik, 2010, p. 1) and some 5-7% of all anthropogenic CO_2 emissions (Van den Heede & De Belie, 2012, p. 431). A number of alternative materials with cementitious properties are available and can be used to replace a proportion of the OPC in a concrete mix. The two most common cement replacement materials are PFA and GGBS. PFA is produced from coal fired power stations whilst GGBS is a by-product of primary steel production. Both products have much lower carbon emissions per kilogram than OPC and hence their use is often cited as a way to reduce the embodied carbon of concrete (Darby, 2014). There are other cement replacements available such as limestone fines or silica fume, however these have not been considered here since they do not arise in the case studies and they are less commonly used in the UK than GGBS and PFA (Habert, 2013).

The scenario uncertainty identified through the literature review for concrete was in relation to the assumptions made about end of life treatment. In the three expert elicitation conducted for concrete, one expert proposed that the location where concrete is mixed or batched should be included since ready mixed concrete (concrete batched at the concrete works) would undergo additional transport compared to concrete batched on site.

In the process of compiling carbon factors for the scenarios identified through the initial literature review and elicitation, a further source of uncertainty was identified relating to whether concrete in landfill is assumed to undergo re-carbonation. As this was only identified after the elicitations had been conducted, it was not possible to include expert perspectives. However, a preliminary quantitative comparison suggested that the effect of this assumption is not insignificant and hence it was included in the final diagram and subsequent analysis.

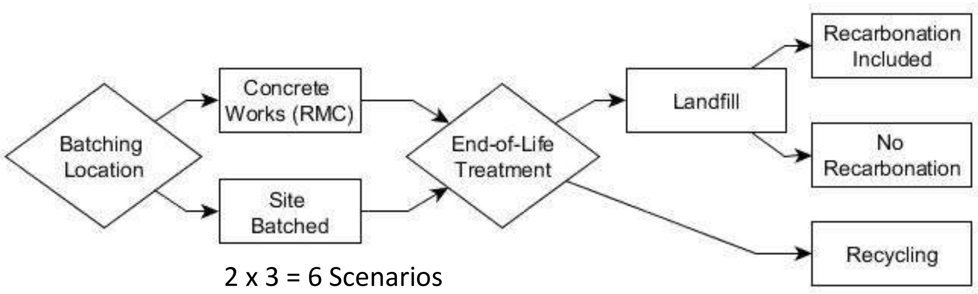


Figure 6-16: Decision tree depicting the main sources of scenario uncertainty for the embodied carbon of concrete. RMC = ready mixed concrete.

The sources of scenario uncertainty identified affect the carbon factors for the transport of concrete after it has been mixed or batched (module A4) and for the end of life treatment (modules C1-4 and D). The raw material extraction (A1) and transport (A2) are assessed separately for each of the main constituent materials of concrete in sections 6.2.6.1 to 6.2.6.3 above and are not included here. The production of concrete is assumed to be unaffected by the scenario uncertainties unidentified and so a single value of 11 kgCO2e/m3 (Ecoinvent, 2013 in Darby, 2014, p. 65) has been used for all scenarios. The values derived for each scenario are presented in Table 6-19

Table 6-19: Carbon factors used to model the scenario uncertainties identified for concrete. The table includes transport from the concrete batching location to the site (module A4 according to EN 15804) and for demolition (C1), transport (C2) and processing (C3) of waste and final disposal (C4) at end of life as well as benefits beyond end of life (D) for recycling of concrete.

Scenario	Batching location	End of life	Recarbonation	Carbon Factor (kgCO₂e/tonne)							
				A4[1,2]	C1[3]	C2[4]	C3	Source/ Notes	C4	Source/ Notes	D[4]
Conc-1	RMC	L.f.	C.	2.73	5.60	1.70	0.00	a	-40.00	3, b	0
Conc-2			N.C.	2.73	5.60	1.70	0.00	a	6.70	3, 5	0
Conc-3		Recy.	N/A	2.73	5.60	1.70	2.40	4	0.00	3	-5.3
Conc-4	S.B.	L.f.	C.	0.00	5.60	1.70	0.00	a	-40.00	3, b	0
Conc-5			N.C.	0.00	5.60	1.70	0.00	a	6.70	3, 5	0
Conc-6		Recy.	N/A	0.00	5.60	1.70	2.40	4	0.00	3	-5.3

Notes:

RMC = Ready mixed concrete
S.B. = Site batched concrete
L.f. = Landfill
Recy = Recycling
C = Re-carbonation of concrete in landfill is included
N.C. = No re-carbonation included

a. It has been assumed that concrete sent to landfill undergoes no further processing
b. The amount of carbonation is estimated based on the data from 4 and adjusted to reflect 100% landfill (compared to 10% modelled in 4)

Sources:

1. Department for Environment, Food and Rural Affairs (2015)
2. Mineral Products Association (2013, p. 7)
3. PE International (2012a, p. 5)
4. PE International (2012b, p. 5)
5. Darby (2014, p. 75 Table 3-20)

6.2.6.4.1 Batching Location

The carbon factors for transport to site have been calculating using the same approach as for the transport of aggregates, cement and SCMs. Ready mixed concrete (RMC) is usually locally sourced due to practical constraints on the length of time before the concrete starts to go off or set. The average transport distance of RMC in 2012 was just 12km (Mineral Products Association, 2013, p. 7) and so the carbon factor is based on a 24km round trip from the concrete works to the site. The emissions per tonne and kilometre are taken from the most recently available UK government carbon factors (Department for Environment, Food and Rural Affairs, 2015). The MPA has stopped publishing average distances for RMC and pre-cast concrete separately in their annual sustainability report and now only provides an average for all concrete types which, in the most recent report was 46 km (Mineral

Products Association, 2017a, p. 7). However, since pre-cast is typically transported much further than RMC (Mineral Products Association, 2013, p. 7), this average value is not appropriate for in-situ poured concrete.

For concrete that is batched on site, the only transport emissions that occur are to bring the raw materials (aggregates, cement and SMCs) to site (module A2). The uncertainty associated with these emissions is assessed in sections 6.2.6.1 to 6.2.6.3 above.

6.2.6.4.2 End of Life

The most comprehensive data that was identified for the end of life carbon emissions from concrete was found to be a series of reports produced by PE International for the British Construction Steelwork Association (BCSA). These reports detail emissions using the modularity principle of EN 15804, but assume that 90% of the concrete is recycled and 10% sent to landfill. It was therefore necessary to alter the figures to reflect the scenario where all concrete is sent to landfill. This only affects the carbon factors for the waste processing (C3) and final disposal (C4) and the benefits beyond end of life. The method used by PE International assumes that some re-carbonation of the concrete will occur in landfill. During carbonation, calcium hydroxide reacts with CO_2 to form calcium carbonate and water (Chang & Chen, 2006, p. 1760). The process is affected by the amount of surface area of the concrete that is exposed to a source of CO_2 such as air (De Saulles, 2013). Darby has assessed the carbonation rate of concrete during the life of the building to be around 2 $kgCO_2$/tonne (2014, p. 73). He concludes that this is negligible compared to the overall carbon factor for concrete and makes no allowance for carbonation which occurs at the end of life in landfill.

For concrete that has been broken up during demolition, the greater surface area is likely to lead to increased carbonation rates. The PE International data reports that for the scenario where 10% of the concrete (i.e. 100 kg of every tonne) is sent to landfill, carbonation results in 4 $kgCO_2$ being absorbed per tonne of concrete (i.e. per 100kg sent to landfill). This would give a value of 40$kgCO_2$/tonne if all the concrete were sent to landfill. This figure is higher than an estimate by De Saulles, who calculated that 30 $kgCO_2$ would be absorbed per tonne of crushed concrete (2013, p. 1). However, the values are of the same order of magnitude.

It should be noted that the data in Table 6-19 are for concrete only and do not include reinforcement. The PE International data for concrete only are based on C50 concrete (2012a, p. 5), which is higher strength than the concretes considered in the case studies here. Additional data is available for lower strength concrete but this included reinforcement which has been excluded here. The concrete strength only affects the carbonation rate reflected in module C4 and therefore the value in Table 6-19 for this module is taken from the data for RC30 concrete (PE International, 2012b, p. 5).

For the scenario where re-carbonation is not accounted for, data was taken from Darby. His results give an aggregated figure for all the end of life modules (C1-4). For comparison, the values for C1 and C2 given in the PE International report were applied and the value for C4 was then calculated such that the sum of C1, C2 and C4 is equal to Darby's estimate of 15.6 kg CO_2e/tonne for disposal in landfill.

For the recycling scenario, the data from the PE International report are used unaltered. In other words, in scenarios Conc-3 and Conc-6, a recycling rate of 90% is assumed.

The data in Table 6-19 have been plotted graphically in Figure 6-17. The carbon factors have been combined with carbon factors for modules A1 and A2 for aggregates and cement. Rather than including the all the different scenarios for aggregates and cement here, the results are plotted using just the carbon factors for aggregate and cement from the scenarios Agg-1 and Cement-1, details of which can be found in section 6.2.6.1 and 6.2.6.2. This has been done to allow the effects of the sources of scenario uncertainty that relate only to concrete, identified in Figure 6-16, to be analysed independently from the sources of scenario uncertainty affecting aggregates and cement. The combined effects of all uncertainties affecting concrete, including aggregates, cement and SCMs, are assessed in section 7.3.

The quantities of aggregate and cement are based on a specific mix design used in one of the case studies and are shown in Table 6-20.

Table 6-20: Quantities of aggregate and cement per cubic meter of concrete for an illustrative mix of C32/40 ready mix concrete

Material	Mass per m^3 (kg)
Cement (OPC)	336
Aggregates	1829
Concrete	2340

The elicited judgements of statistical uncertainty are included in Figure 6-16 in the form of error bars applied to the total cradle to grave carbon factor (modules A-C). The highest estimates of statistical uncertainty that were elicited have been used which were an upper bound of +25% and a lower bound of -20%.

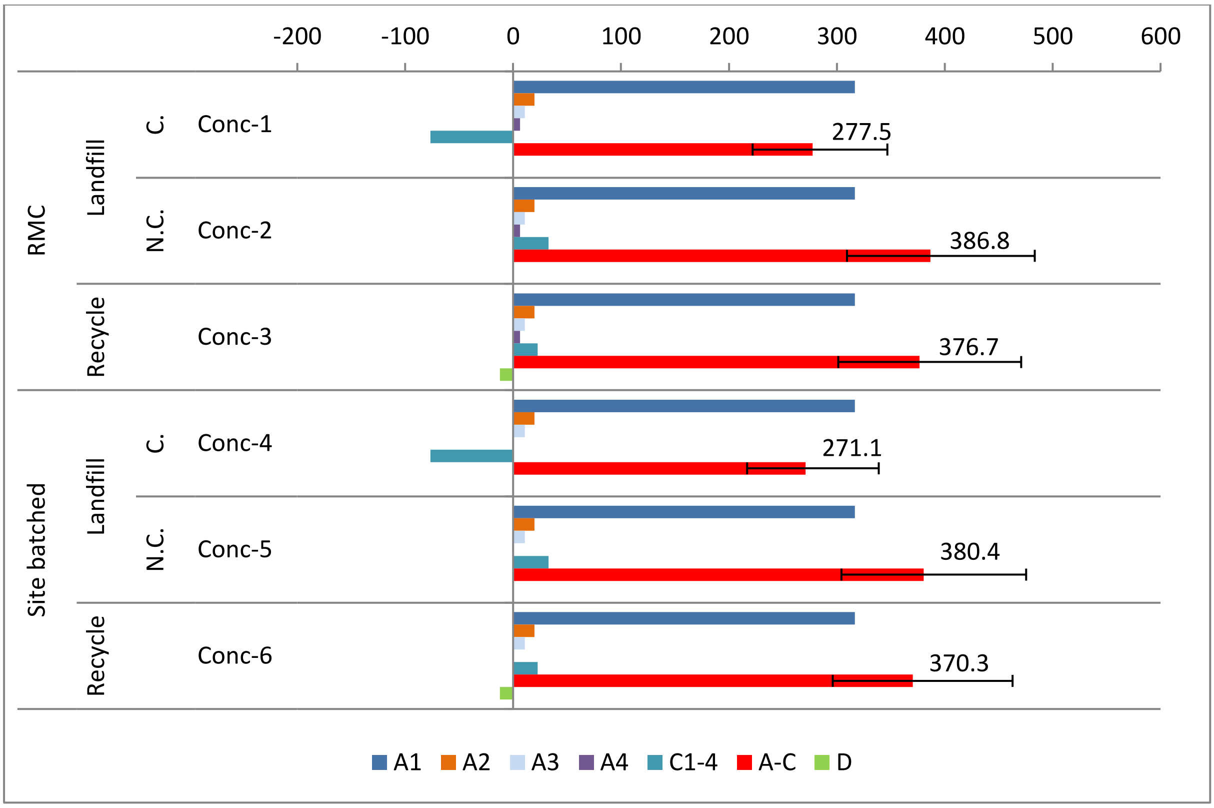


Figure 6-17: Uncertainty in the carbon factor for concrete based on elicited expert judgement.

Notes:
The scenarios numbered Conc-1 to Conc-6 illustrate the effect of relevant sources of scenario uncertainty whilst the error bar applied to the total carbon factor for modules A-C illustrates the estimated effect of sources of statistical uncertainty.

Scenario classifications:
RMC = Ready mix concrete
C. = Re-carbonation of concrete in landfill is included
N.C. = No re-carbonation is included

Life cycle modules according to EN 15804 (British Standards Institution, 2014a):
A1 = Raw material supply
A2 = Transport of raw materials
A3 = Production/manufacture of concrete
A4 = Transport of concrete to site
C1-4 = Demolition, waste transport, processing and final disposal
D = Benefits beyond the end of life (re-use, recovery, recycling etc.)

Of the sources of scenario uncertainty included here, those relating to the end of life treatment of concrete have the greatest impact on the embodied carbon factor for the life cycle stages included here. It is important to note however that these results represent just one combination of scenarios for aggregates and cement. The preceding assessments of the uncertainty affecting embodied carbon factors of these materials add further uncertainty to the total cradle to grave embodied carbon of concrete. The effects on the overall uncertainty of combining different materials into composites such as concrete are demonstrated and discussed in two of the material comparison case studies in the following chapter.

7 Uncertainty Assessment of Comparative Embodied Carbon Assessments: Case Study Results

The results of the uncertainty assessments of carbon factors for selected materials presented in Chapter 6 have been used to assess the effects of uncertainty on comparative embodied carbon assessments of building elements. Three case studies have been selected and designed to show the effect that uncertainty can have on design decisions to reduce embodied carbon and thus the results and discussion in this chapter fulfil objective four of the research.

All three case studies involve the comparison of the embodied carbon of two different materials or products that are close substitutes to fulfil the same function. Material substitution is a strategy for reducing embodied carbon which has been frequently recommended or analysed in academic research (Pomponi & Moncaster, 2016) and has been the primary approach trialled by Sainsbury's for embodied carbon reduction in supermarkets.

The analysis here only considers the materials which perform the stated function and excludes all other elements of the building. It is likely that in some instances, changing the material specification for the specified function may affect other elements of the building. For example, changing the structural frame design will have implications for other building elements such as the foundations. However, the goal of this analysis is to demonstrate the effect of uncertainty on the carbon assessment results for each material rather than to attempt to provide a comprehensive and conclusive comparison of the two alternatives. Introducing more materials into the uncertainty assessment adds complexity to the process of identifying and communicating which uncertainties are attributed to which material. Thus it was deemed appropriate to exclude other materials here, whilst acknowledging that in practice, comparative assessments must take account of such consequential changes.

7.1 Case Study 7-1: Steel vs. Glulam Structural Frame

Figure 7-1: Sub-section of the structural frame for a supermarket for which the embodied carbon of two alternative materials is assessed in this case study

This case study compares the embodied carbon of a glulam timber frame with an alternative steel design. The design data are taken from Sainsbury's Melton Road Supermarket in Leicester. The actual frame design for the Leicester store was a hybrid solution involving the use of glulam structural members for the sales area frame and steel frame for the warehouse. For this comparative assessment, only a sub-section of the glulam timber frame for the sales area is assessed, compared to a steel frame design for a sub-section of the same dimensions. This was done to ensure a fair comparison between the two frame alternatives. Because the glulam timber structural beams and columns are joined with steel plates, conducting an assessment of the entire building frame, including the steel frame in the warehouse would make it difficult to determine what proportion of the total carbon emissions for the steel to allocate to the glulam frame design. In the quantity data obtained from the BIM model, there was no clear distinction between the steel jointing plates for the glulam frame and the steel plates that formed part of the steel frame to the warehouse area. By performing a separate quantity take-off (see section 4.3 for the an explanation of this term) for the sub-section of frame shown in Figure 7-1, it was possible to ensure that only the steel connection plates for the glulam frame were included.

Glulam has been used for the structural frame of an increasing number of supermarkets and large retail stores in the UK. It is often associated with flagship projects intended to showcase environmental sustainability, such as Sainsbury's stores at Greenwich or Dawlish and Tesco's Ramsey store (Ijeh, 2014). In an unpublished assessment of Sainsbury's Dartmouth store, the glulam frame was estimated to have 57% less embodied carbon than a steel alternative, leading to a 27% saving on the total embodied carbon for the building (dCarbon8, 2008). Therefore, this case study illustrates how uncertainty affects the estimation of potential embodied carbon savings that are achievable by using glulam as an alternative material to steel.

Material quantities were taken from the structural BIM models for Sainsbury's Leicester store which were provided by the architect. The quantities of steel and glulam in each design are shown in Table 7-1.

Table 7-1: Material quantities for two alternative structural frames matching the dimensions shown in Figure 7-1

Material	**Material Quantity**			
	Glulam Frame		**Steel Frame**	
	Volume (m^3)	**Mass (tonnes)**	**Volume (m^3)**	**Mass (tonnes)**
Steel (7850 kg/m^3)	0.17	1.33	1.38	10.83
Glulam (490 kg/m^3)	33.72	16.52	0	0

7.1.1 Scope and Boundaries

In this case study, it was assumed that neither of the structural frames requires maintenance or replacement during the lifecycle of the store, which is modelled as 25 years (see Richardson et al. (2014) and section 4.4.4 for justification of this assumption). Therefore, modules B1-5, relating to recurring embodied carbon during the use phase, have been omitted from the comparison. In practice, either frame option may require some maintenance in the form of paint or preservative treatment, however prior studies have shown the impact of maintenance to be negligible compared to other life cycle stages (Kofoworola & Gheewala, 2009) and its exclusion here is therefore not expected to impact the validity of the results.

The carbon factors for steel listed in Table 6-7 and Table 6-8 and those for Glulam in Table 6-11 and Table 6-12 in the previous chapter were used to model each of the scenarios for the two frame options. Since the hybrid frame option contains both steel and glulam, it would be necessary to model 210 different scenarios; 10 different glulam scenarios for each of the 21 steel scenarios (21 x 10 = 210 scenarios in total). However, the comparison of the two options was simplified by omitting the steel from the hybrid option and reducing the total amount of steel in the steel frame option by the equivalent amount. In this way it was only necessary to model 10 scenarios for the embodied carbon of the glulam in the hybrid frame option and compare these to the 21 scenarios for the steel frame option.

7.1.2 Results

The results of the uncertainty assessment of the comparative embodied carbon assessment of the two frame options are shown in Figure 7-2 below. The results for the steel frame have been grouped together by the assumption about production route, since this has the greatest impact on the results. For the results based on industry average production, a further sub-grouping has been applied based on whether the system expansion or recycled content approach has been used.

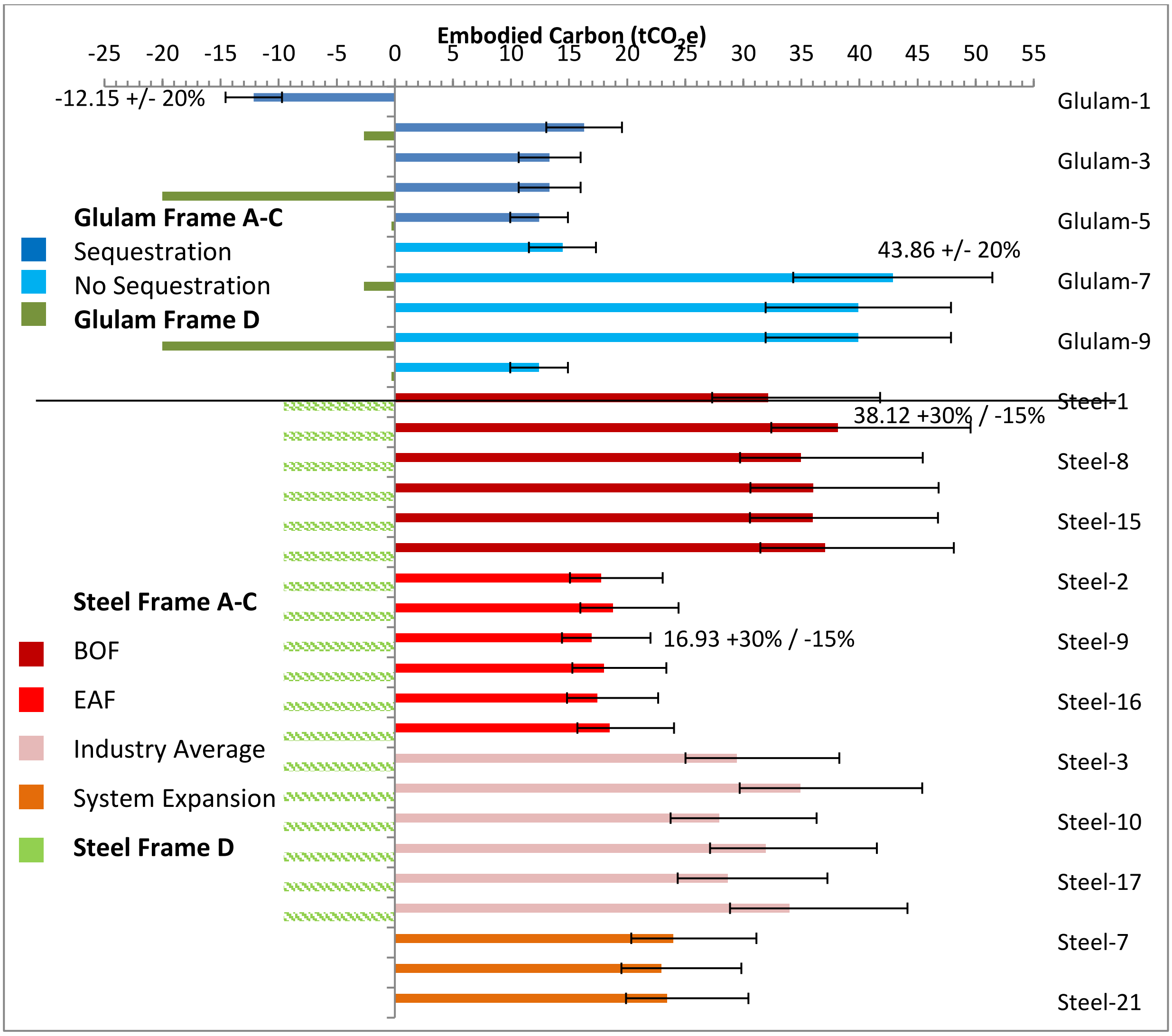


Figure 7-2: Assessment of the effects of scenario and statistical uncertainty on the comparative embodied carbon assessment of glulam and steel structural frame options for a supermarket.

Notes:

Results are for a portion of the building measuring $72m^2$

The scenarios numbered Glulam-1 to Glulam-10 and Steel-1 to Steel-21 illustrate the effect of relevant sources of scenario uncertainty as indicated. The error bars applied to the total cradle to gate embodied carbon represent statistical uncertainty. The values shown for module D are indicative estimates included to illustrate how the recycled content and system expansion approaches differ in their treatment of these impacts. In reality further variation and uncertainty between the different scenarios using the recycled content method would be expected.

Scenario classifications:

Steel-1-7: No allocation to co-products
Steel-8-14: Physical allocation
Steel-15-21: Economic allocation
Steel-1, 8 & 15: EU BOF Steel
Steel-4, 11 and 18: Global BOF Steel
Steel-2, 9 and 16: EU EAF Steel
Steel-5, 12 & 19: Global EAF steel
Steel-7, 14 and 21: Industry average with system expansion (for recycling)
Steel-1, 4, 8, 11, 15, 18: Recycled content
Glulam-1 & 6: Landfill with low decay
Glulam-2 & 7: Landfill with high decay
Glulam-3 & 8: Incineration
Glulam-4 & 9: Energy recovery
Glulam-5 & 10: Recycling

Life cycle modules according to EN 15804 (British Standards Institution, 2014a)**:**

A – C: raw material supply, transport, manufacture, transport to site, demolition and disposal.
D: benefits beyond the life cycle
Construction (A5) and use (B) are excluded

The results of the uncertainty assessment show that the glulam frame has a greater overall range of possible values than the steel frame. The extremes of the range for the glulam frame are -14.6 (Glulam-1) and 52.6 tCO_2e (Glulam-7) when both scenario and statistical uncertainties are considered, whilst for steel they are 14.4 and 49.6 tCO_2e (Steel-9 and Steel-4 respectively).

By breaking these ranges down into specific scenarios, each based on a defined set of assumptions as has been done here, it is possible to see which sources of uncertainty are causing this variability and also the relative magnitude of the effect of one source of uncertainty compared to another. For example, it can be seen that in general, within a particular group of scenarios assigned the same colour in Figure 7-2, there is relatively little variation compared to the difference between one group and another. The steel scenarios are grouped according to the assumption made about the production route. This indicates clearly how important this assumption is when comparing the steel frame to the glulam alternative. The choice of production route has a greater effect on the difference between the embodied carbon of the steel and the glulam for a given glulam scenario than either the choice of allocation method (for co-products) or the choice of production location.

Similarly, for the glulam frame, the choice of whether to credit sequestration can be seen to have a much greater effect on embodied carbon than most of the different end of life assumptions. The exceptions to this are the two alternative assumptions about landfill. If the timber is assumed to be sent to landfill, the assumed decay rate is a very important source of uncertainty. Assuming a low decay rate leads to a scenario where carbon sequestered in the timber is effectively stored underground and is not released, or in the case that no credit is given for sequestration, then the end of life emissions are never-the-less greatly reduced when compared to other waste treatment options. By contrast, of a high rate of decay is assumed, then the landfill option is seen to lead to slightly higher emissions since a proportion of the carbon is assumed to be emitted as methane which is has a higher global warming potential the CO_2.

The difference between the embodied carbon values for the two frame options for each combination of scenarios has been calculated using Equation 7.1 and the results plotted in Figure 7-3 below.

$$Embodied\ Carbon\ Difference = EC_{Steel-x} - EC_{Glulam-y} \qquad \text{Equation 7.1}$$

Difference in embodied carbon between steel and glulam alternatives

Where $EC_{Steel-x}$ and $EC_{Glulam-y}$ are the embodied carbon values for the steel and glulam frames for scenarios x and y.

When considering the comparison of the two frame options as depicted in Figure 7-3, the effect of scenario uncertainties is particularly stark. If the lowest value for glulam, Glulam-1, is compared to the highest value for steel, Steel-4, then using the glulam frame is seen to give a saving of 64.1 tCO_2e. At the other extreme, comparing the most favourable scenario for steel with the least favourable for glulam (Steel-9 and Glulam-7), the glulam option apparently leads to an increase in embodied carbon of 38.2 tCO_2e. This is a range of over 100 tCO_2e.

To improve the clarity of the results in Figure 7-3, statistical uncertainty has been represented by error bars applied only to the highest and lowest data points. The upward error bars represent the greatest possible increase in the difference between the two options (as calculated by Equation 7.1) by comparing the estimated upper limit for glulam (+20%) with the estimated lower limit for steel (-15%). Conversely, the downward error bars are the comparison of the lower limit for glulam (-20%) with the upper limit for steel (+30%). Such error bars can be applied to all the data points but only the extremes are plotted and all others would fall within that range.

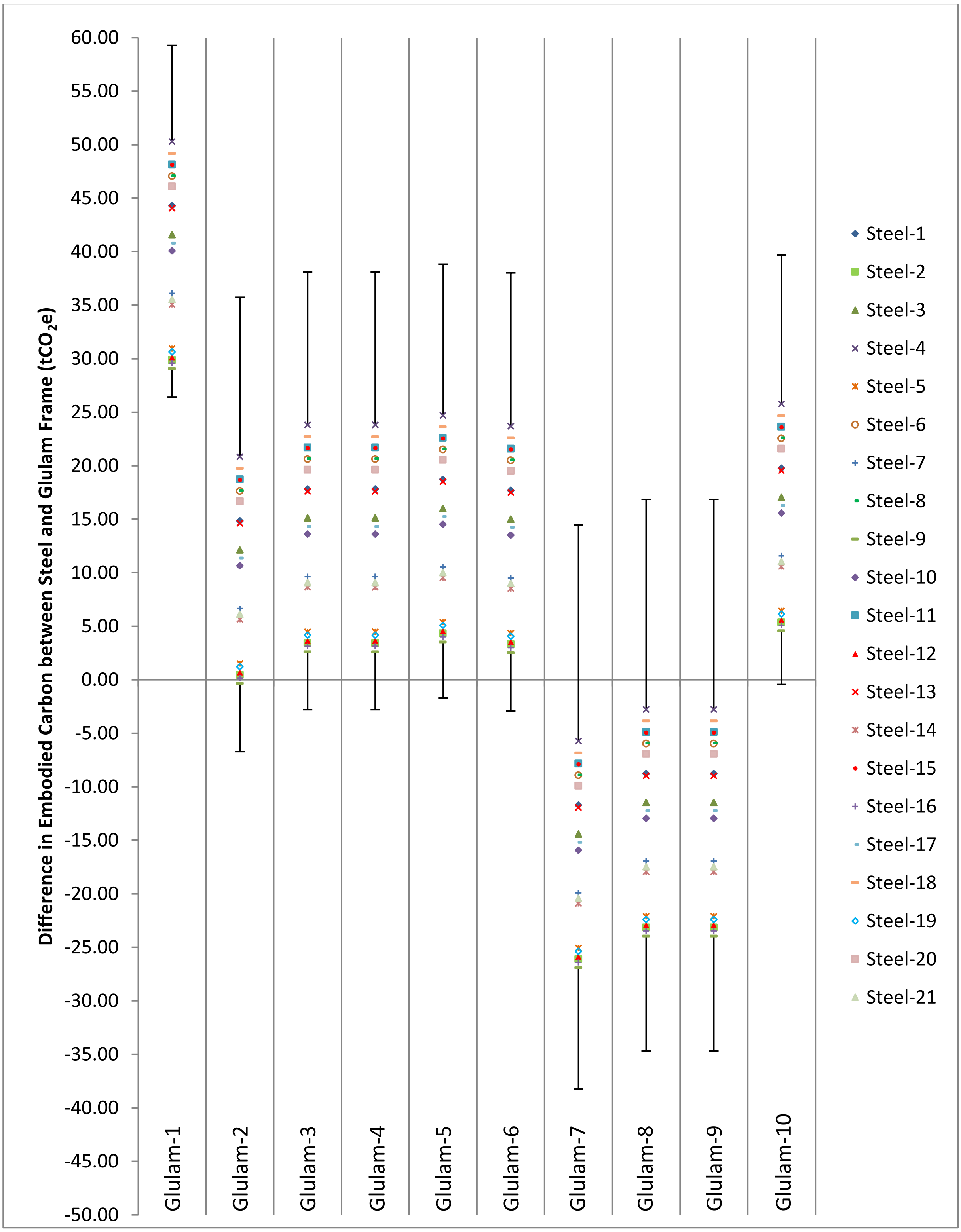


Figure 7-3: Difference in embodied carbon between steel and glulam alternatives for each combination of scenarios modelled as part of the uncertainty assessment. Modules A-C (cradle to grave) only. See notes for Figure 7-2

From Equation 7.1, a positive value means that the glulam frame has lower embodied carbon than the steel frame. Of the 210 data points plotted in Figure 7-3, 146 are positive and 64 are negative Therefore, for just under 70% of scenario combinations modelled, the use of glulam for the frame results in an embodied carbon saving versus the steel frame. Of the 64 cases where steel has lower embodied carbon, all but one occur when comparing any of the steel scenarios with scenarios 7-9 for glulam. That is, where sequestration is not credited and the timber is assumed to be either incinerated, sent to energy recovery or landfill with a high rate of decay assumed. The one exception to this occurs when Glulam-2 (sequestration credited and landfill with high decay rate assumed) is compared with Steel-9 (EAF steel sourced from the EU with physical allocation applied to co-products and the recycled content method used), whereby the glulam has embodied carbon that is 0.36 tCO_2e higher than the steel.

It can be seen that glulam scenarios 2-5 and 10 all have downward error bars which extend below the x-axis. Therefore, if estimates of statistical uncertainty are included then more of the scenario combinations could lead to results where the glulam frame has greater embodied carbon than the steel. This is an important result to take into consideration when evaluating the possible embodied carbon savings that can be achieved by using glulam instead of steel. If the embodied carbon factor of steel is estimated using data specific to the EAF process, then even with the inclusion of sequestered carbon in timber, inefficiencies in the timber production, or other factors leading to statistical uncertainty, could negate any carbon saving.

The scenario uncertainty results are presented in Figure 7-4 in terms of the percentage savings achieved through the use of glulam versus the embodied carbon of the steel frame option. These sources of uncertainty lead to a range of 172% to -159%. In other words, the most optimistic combination of assumptions (from the point of view of maximising possible savings) suggests that the glulam frame saves 172% of the embodied carbon of the steel frame. The most pessimistic combination of assumptions suggests that the glulam frame results in embodied carbon that is 159% higher than the steel frame. This is a very wide range of possible outcomes, which is why this research proposes and promotes modelling and considering each of the individual scenarios. Presenting the results in this way offers greater insight than could be achieved if only the quantitative range is known. The results encourage decision makers to consider on what basis different assumptions or methodological choices can be justified.

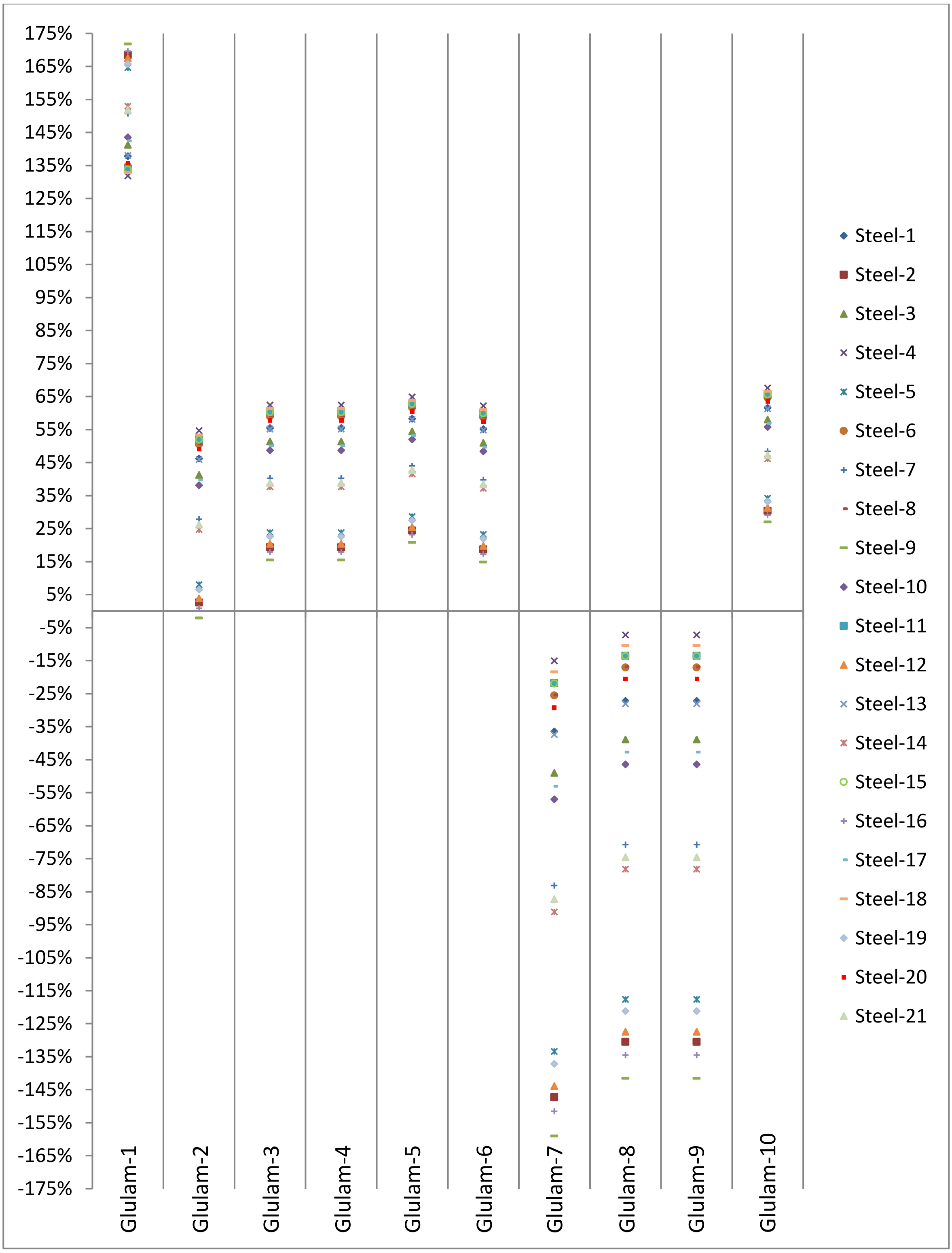


Figure 7-4: Percentage reduction in embodied carbon for the glulam frame compared to the steel frame for each combination of scenarios modelled as part of the uncertainty assessment. Modules A-C (cradle to grave) only. See notes for Figure 7-2

The benefit of modelling uncertainties in this way is that the results allow designers and decision makers to understand the relative impact of different sources of uncertainty. The implications and justifications for making different assumptions about a given material can be assessed. There may be scope to undertake certain measures which make a particular set of assumptions more reasonable or defensible in order to mitigate particular sources of uncertainty In this way, some of the scenario uncertainty could be mitigated, leading to greater confidence in embodied carbon results. This is discussed further in Chapter 8 (see section 8.2.6).

7.2 Case Study 7-2: Insulated Timber Cassette vs. Insulated Steel Deck Roof

The second of this set of case studies compares a lightweight steel roof with an alternative timber cassette. The comparison is based on data from one of Sainsbury's supermarkets built in 2014 which had a total insulated roof area of 9,147 m^2. The uninsulated canopies around the perimeter of the buildings are not included. The steel deck roof is a manufactured composite roof system comprising a trapezoidal profiled steel sheet inner layer with polyurethane foam insulation (to fill the profile) and a PVC waterproof outer layer. The roof is supplied in prefabricated panels which are screwed to light-gauge steel purlins that are, in turn, supported from the main roof beams. The timber cassettes are also prefabricated and comprise an outer sheet of birch plywood, timber I-beams and glulam beams, for rigidity, with mineral wool insulation between and an inner sheet of oriented strand board. Each cassette is framed with softwood which forms the connection to the adjacent cassettes. The figures below show indicative cross-sections of the two types of roof.

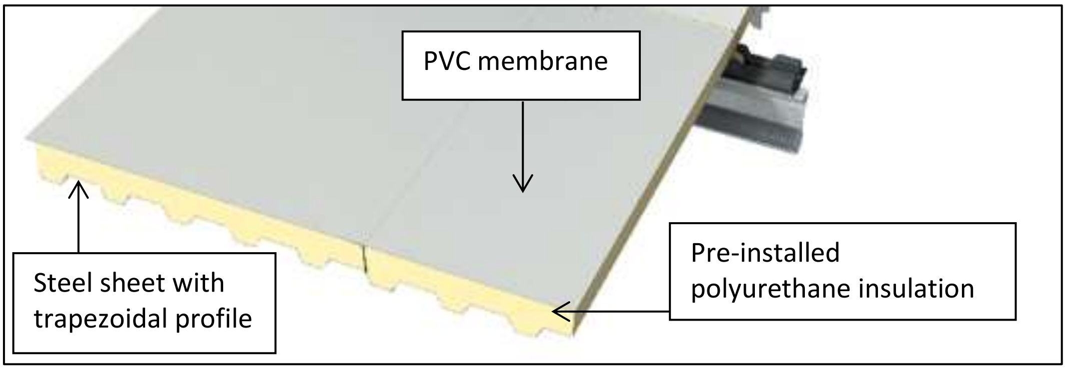
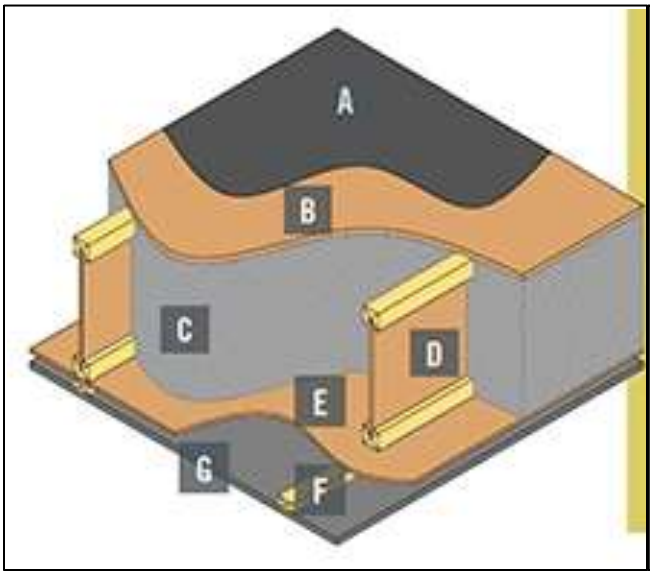


Figure 7-5: A section of a composite insulated steel deck roof system (Source: Kingspan)



A = External weatherproof membrane

B = Birch ply outer sheet

C = Mineral wool insulation

D = Timber i-beams

E = Oriented Strand Board (OSB) inner sheet

F & G = Plasterboard and battens – not applicable to this case study

(Softwood framing and internal glulam beams not shown)

Figure 7-6: Section of an insulated timber roof cassette (Source: Stewart Milne Timber Systems)

For both roof systems, the scope of the comparative assessment is limited to the roof itself. For the timber cassettes, only the materials in the roof cassettes are included. For the steel roof, the assessment covers the pre-insulated deck and also the roof purlins. Purlins are a form of secondary steel which span between the main beams of the frame and whose primary function is to support the roof. The timber cassette roof is supported by the main roof beams and so does not require purlins. It is therefore necessary to include the purlins in this assessment of the steel deck.

In both cases, the fixings required to secure the roof to the frame and sundry items required to prevent water ingress and ensure airtightness were excluded. This was done on the basis that their embodied carbon impact was expected to be both very similar between the two types of roof and also relatively very small compared to the main roof materials.

The assessment includes all cradle to grave life cycle stages except the construction stage and the use stage. Construction is excluded due to lack of data specific to the particular materials and the use phase is excluded on the basis that the service life of both roof systems exceeds the typical service life of a supermarket. The benefits beyond the end of life (module D) were assessed for both roof systems but were not included in the calculation of estimated emissions savings. In accordance with EN 15978 and EN 15904 (British Standards Institution, 2011a, 2014a) these emissions savings are credited to a subsequent product system and so are excluded here to avoid double counting.

Carbon emissions from transportation (A2 for raw materials and A4 for finished product) were estimated using average road transport distances from the Department for Transport. The manufacture of the panels (A3) is included based on estimates of typical fabrication processes for sheet steel and including wastage rates for the individual constituent materials based on data from the Waste Resources Action Programme (2013). All other carbon factors used are those derived in the relevant sections of Chapter 6.

The material quantities for the two roof systems, including the wastage rates assumed for each material, are given in Table 7-2 and Table 7-3.

Table 7-2: Material quantities for insulated steel deck roof

	Quantity	**% Waste[1]**
Roof Area	9147 m^2	n/a
Steel sheet	6.86 m^3	20
Steel purlins	7.7 m^3	20
Polyurethane insulation	517.8 m^3	15
PVC outer skin	13.7 m^3	5

1 WRAP Net Waste Tool Baseline wastage rates **(2013)**

Table 7-3: Material quantities for insulated timber cassette roof

	Quantity	**% Waste[1]**
Roof Area	9147 m^2	n/a
Birch ply	60.2 m^3	10
Glulam	65.7 m^3	10 10
I-Beam	123.7 m^3	10
OSB	150.4 m^3	10
Softwood	33.1 m^3	10
Mineral Wool	1790.6 m^3	15

1 WRAP Net Waste Tool Baseline wastage rates **(2013)**

7.2.2 Results

7.2.2.1 Insulated Steel Deck

The effect of uncertainty on the embodied carbon of the steel deck roof was assessed based on the outcomes from the elicitations for steel and polyurethane, detailed in sections 6.2.2 and 6.2.5 of the previous chapter. The steel for the roof is sheet steel which is manufactured from steel produced via the BOF route, due to the higher impurities present in EAF steel which would weaken the sheet (World Steel Association, 2011). The scenarios identified in Figure 6-2 which relate to EAF steel were therefore excluded from the assessment carried out for this case study. The scenarios for industry average steel were included, since the steel industry promotes the use of industry average data for all steel types (for an explanation of this, see section 6.2.2.4). However, industry average data was only available for the system expansion method of accounting for recycling. This reduces the number of steel scenarios from 21 to 9 (the original numbering from section 6.2.2 has been retained to allow comparison). For polyurethane, both the scenarios identified in the elicitation were included. The PVC outer layer was not assessed for uncertainty but was included in the embodied carbon assessment, based on EPD data which assumes the material is sent to landfill (Mapei, 2016). Combining the scenarios for the steel and insulation gives 18 different scenarios that were assessed, as shown in Figure 7-7 which plots the combined effects of the scenario and statistical uncertainty.

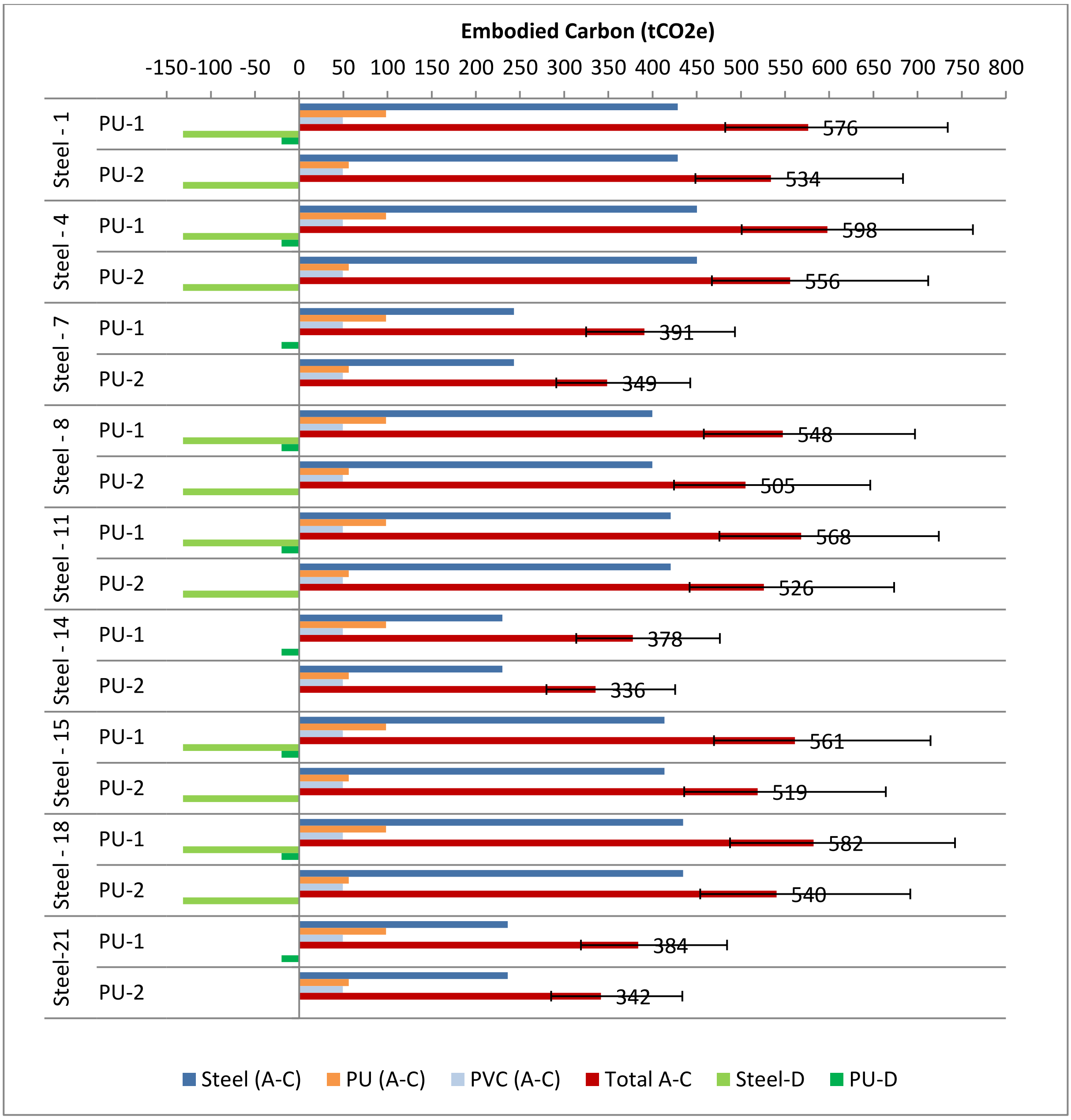


Figure 7-7: Assessment of the effects of sources of scenario and statistical uncertainty on the embodied carbon of an insulated steel deck roof system

Notes:
The scenarios numbered Steel-1 to Steel-21 and PU-1 to PU-2 illustrate the effect of relevant sources of scenario uncertainty as indicated. The error bars applied to the total cradle to gate embodied carbon represent statistical uncertainty

Scenario classifications:
Steel-1-7 No allocation to co-products
Steel-8-14 Physical allocation
Steel-15-21 Economic allocation
Steel-1, 8 & 15: EU BOF Steel
Steel-4, 11 and 18 Global BOF Steel
Steel-7, 14 and 21 Industry average with system expansion (for recycling)
Steel-1, 4, 8, 11, 15, 18: Recycled content
PU-1: Insulation incinerated with energy recovery
PU-2: Insulation sent to landfill

Life cycle modules according to EN 15804 (British Standards Institution, 2014a)
A – C includes raw material supply, transport, manufacture, transport to site and demolition and disposal.
D includes benefits beyond the life cycle such as recycling and energy recovery
Construction (A5) and use (B) are excluded

The range of embodied carbon values estimated for the steel roof structure varies from just below 340 tonnes to almost 600 tonnes of CO_2e. When statistical uncertainty is included, the upper bound increases to more than 750 tonnes and the lower bound is below 300 tonnes for the highest and lowest scenarios respectively. The sources of scenario uncertainty for the steel are seen to have the greatest effect on the overall embodied carbon, with the highest value (Steel-4) almost 60% greater than the lowest (Steel-14) for the same PU scenario. By contrast, PU-1 is just 12.5% higher than PU-2 for the Steel-14 scenario and the effect is less for the other steel scenario where PU contributes proportionately less to the combined total.

7.2.2.2 Timber Cassettes

The timber cassette roof contains five different types of timber (see Table 7-3 above). The sources of scenario uncertainty identified in section 6.2.3 and depicted in Figure 6-4 gave rise to 10 scenarios representing different combinations of choices or assumptions. These 10 scenarios were modelled for all five types of timber used to construct the cassettes. The mineral wool scenarios depicted in Figure 6-6, were simplified here since it was found that the end of life emissions contributed less than 1% of the total for mineral wool for both alternative scenarios. Therefore, only the landfill scenarios were included since this is current practice (Dunster, 2007). Recycling of mineral wool is not commonly undertaken for construction and demolition waste due to concerns about contamination and the composite nature of timber cassettes increases the likelihood of contamination. In total 20 scenarios were therefore assessed for the timber cassettes. The results of the assessment of scenario and statistical uncertainties for the timber cassettes are shown in Figure 7-8.

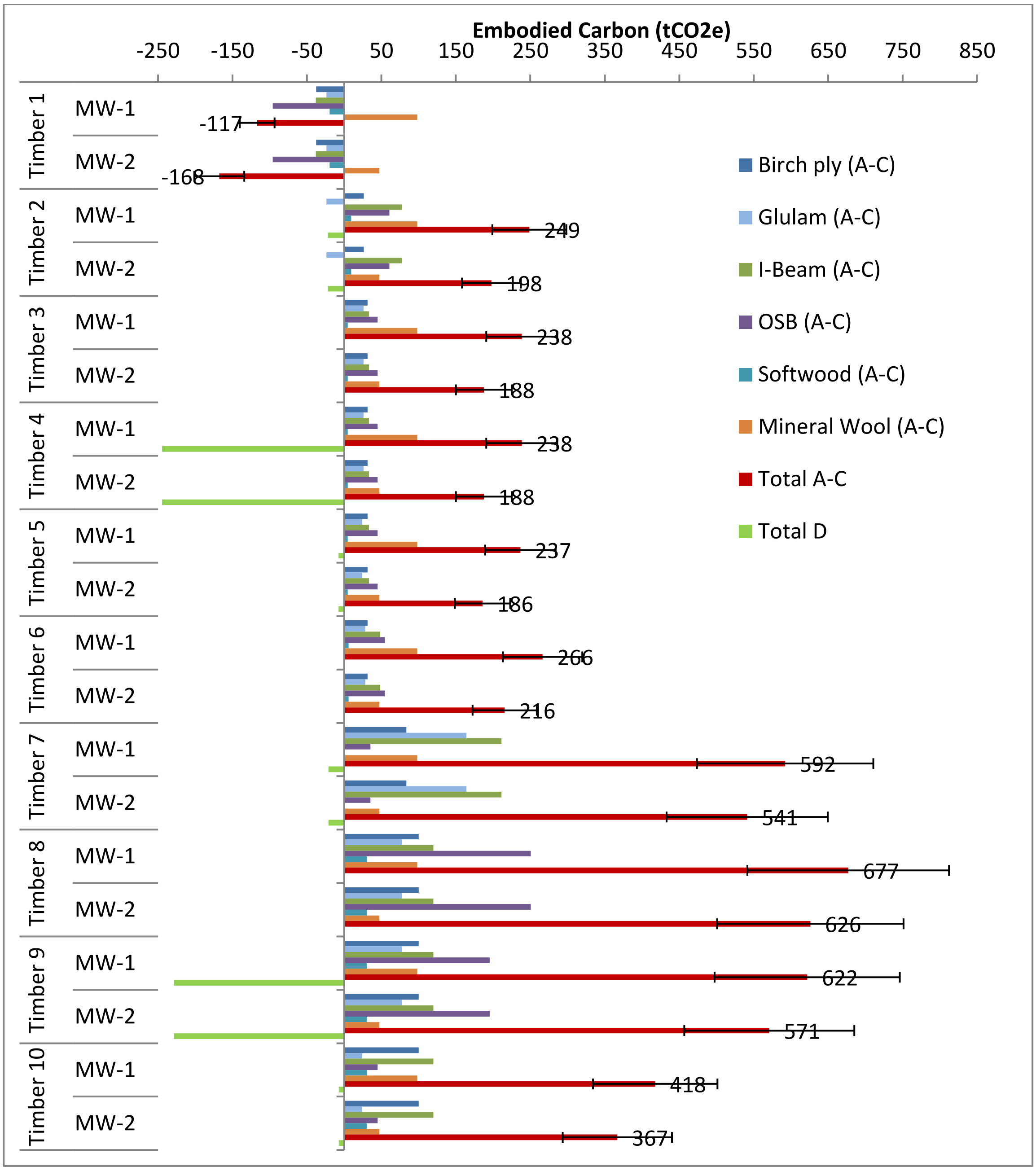


Figure 7-8: Assessment of the effects of sources of scenario and statistical uncertainty on the embodied carbon of a timber cassette roof system

Notes:

The scenarios numbered Timber-1 to Timber-10 and Mineral Wool-1 to Mineral Wool-2 illustrate the effect of relevant sources of scenario uncertainty as indicated. The error bars applied to the total cradle to gate (A-C) embodied carbon represent statistical uncertainty.

Scenario classifications:
Timber-1-5 Sequestered carbon credits included
Timber-6-10 No credit for sequestered carbon
Timber-1 & 6 Landfill with low rate of decay
Timber-2 & 7 Landfill with high rate of decay
Timber-3 & 8 Incineration
Timber 4 & 9 Energy recovery
Timber-5 & 10 Recycling
MW-1: Stone wool; MW-2: Glass wool

Life cycle modules according to EN 15804 (British Standards Institution, 2014a)

A – C includes raw material supply, transport, manufacture, transport to site and demolition and disposal.

D includes benefits beyond the life cycle such as recycling and energy recovery

Construction (A5) and use (B) are excluded

The scenarios for the timber have a much greater impact on the embodied carbon of the timber cassette roof system than the type of mineral wool insulation. The least favourable scenario for timber (Timber-8) results in carbon emissions for the whole roof that are almost 800 tonnes CO_2e greater than the most favourable scenario (Timber-1) for the same mineral wool type. Because of the dominance of timber in the embodied carbon for the whole system, the choice of whether credit is given for sequestered carbon in the growth phase has the most significant impact on the results and is therefore the greatest source of scenario uncertainty.

The following two figures show the estimated embodied carbon reduction (or increase) that is achieved by changing the roof specification from the steel deck to the timber cassette alternative. Figure 7-9 shows the results in absolute terms whilst Figure 7-10 shows the percentage decrease or increase compared to the steel roof.

In a similar way to the previous case study, the comparison of the steel deck and timber cassettes was found to be highly sensitive to the scenario uncertainties identified. For the timber scenarios where sequestered carbon is credited, the timber cassettes always outperform the steel deck in terms of reducing embodied carbon. If credit is not given for sequestered carbon, then the situation is reversed in all but one instance. The timber cassettes have higher embodied carbon except when it is assumed that the timber is sent to landfill with a low rate of decay. In the low rate of decay scenario, most of the carbon sequestered in the timber remains stored as biogenic carbon and is not emitted as CO_2 during the 100-year assessment period.

The absolute values exhibit two distinct clusters of results within each of the timber cassette scenarios. When compared against the results for Steel-7, 14 and 21, where industry average data are used for the steel, the benefit of using timber is much less than when compared against BOF specific steel data. (In the cases where the timber results in higher embodied carbon than the steel roof, the increase is greater when compared with these scenarios). This is not surprising, given that using industry average data gives lower carbon factors than using BOF specific data. In other words, Steel-7, 14 and 21 are more based on more favourable data because of the effect of including EAF steel in the industry averages.

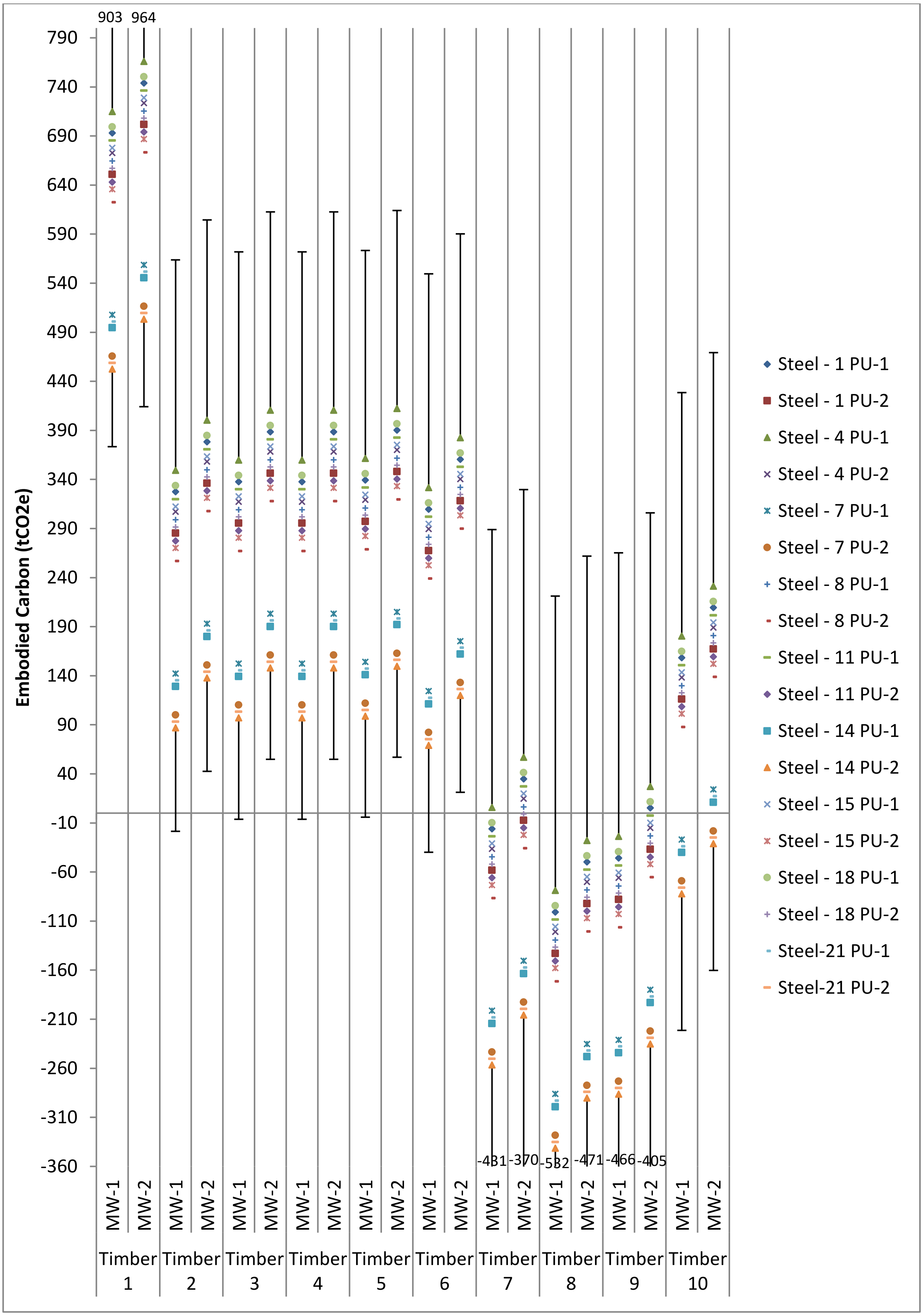


Figure 7-9: Difference in embodied carbon between steel deck and timber cassette alternatives for each combination of scenarios modelled as part of the uncertainty assessment. Modules A-C (cradle to grave) only.

Notes for Figure 7-9:
The scenarios numbered Timber-1 to Timber-10, MW-1 to MW-2, Steel-1 to Steel-21 and PU-1 to PU-2 illustrate the effect of relevant sources of scenario uncertainty for the four material types (MW = Mineral Wool; PU = Polyurethane). The error bars applied to the total cradle to gate (A-C) embodied carbon represent statistical uncertainty. These have been truncated to ensure the y-axis scale allows the markers to be distinguishable. The values shown on the chart indicate the extent of the truncated error bars

Scenario classifications:
Timber-1-5 Sequestered carbon credits included
Timber-6-10 No credit for sequestered carbon
Timber-1 & 6 Landfill with low rate of decay
Timber-2 & 7 Landfill with high rate of decay
Timber-3 & 8 Incineration
Timber 4 & 9 Energy recovery
Timber-5 & 10 Recycling
MW-1: Stone wool; MW-2: Glass wool
Steel-1-7 No allocation to co-products
Steel-8-14 Physical allocation
Steel-15-21 Economic allocation
Steel-1, 8 & 15: EU BOF Steel
Steel-4, 11 and 18 Global BOF Steel
Steel-7, 14 and 21 Industry average with system expansion (for recycling)
Steel-1, 4, 8, 11, 15, 18: Recycled content
PU-1: Insulation incinerated with energy recovery
PU-2: Insulation sent to landfill

Life cycle modules according to EN 15804 (British Standards Institution, 2014a)
A – C includes raw material supply, transport, manufacture, transport to site and demolition and disposal.
D includes benefits beyond the life cycle such as recycling and energy recovery
Construction (A5) and use (B) are excluded

The results are plotted as percentage values in Figure 7-10 and Figure 7-11. The percentages represent the estimated embodied carbon saving achieved by replacing the insulated steel deck with the timber cassettes. The results are split across two figures in order to ensure the individual markers can be distinguished. Figure 7-10 shows positive results, i.e. those results where the timber cassettes are estimated to have lower embodied carbon than the steel. Here it was necessary to truncate the y-axis to fit the results onto one chart. Figure 7-11 shows the negative values, i.e. those combinations of assumptions which result in the timber cassettes having higher embodied carbon than the steel alternative.

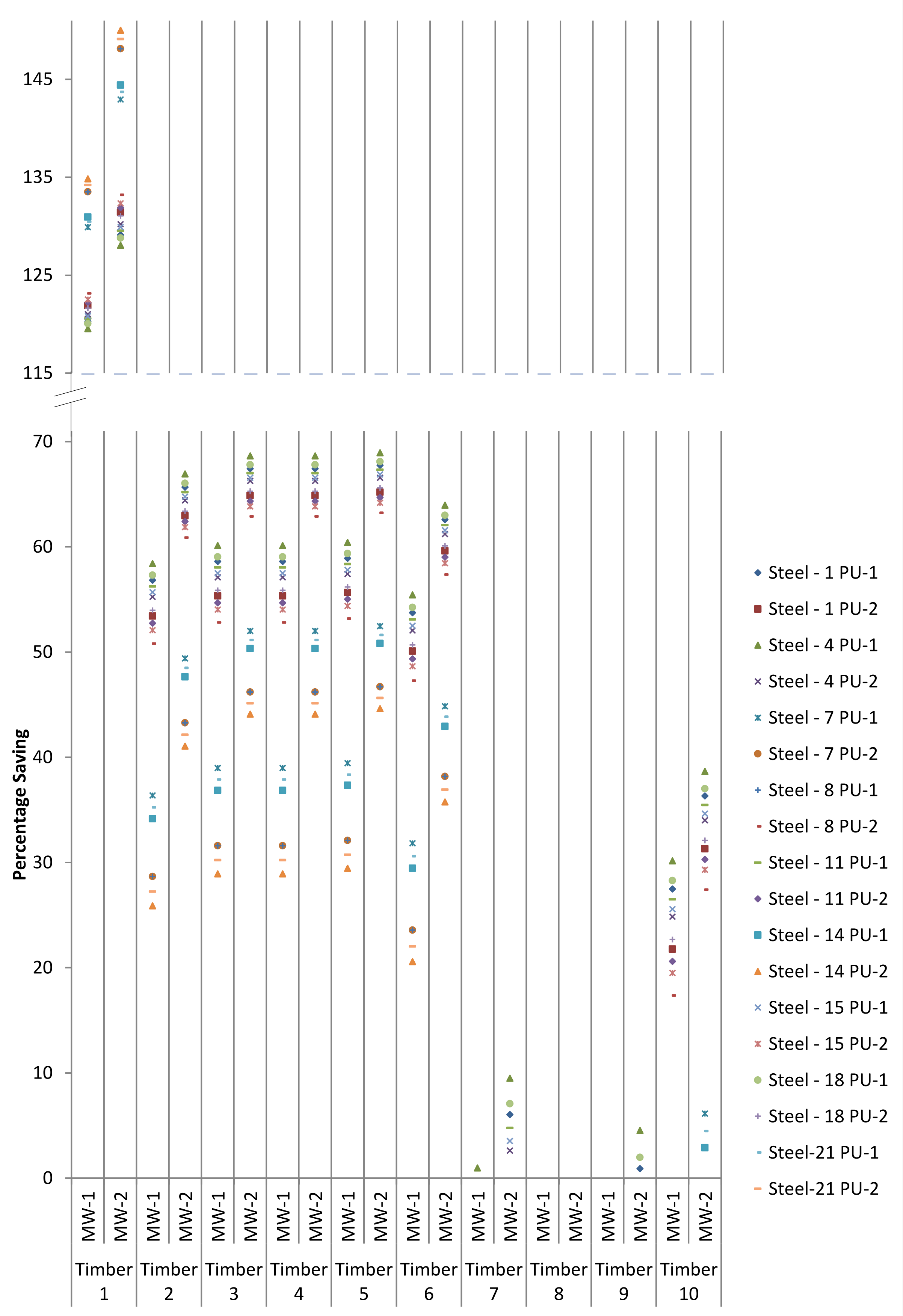


Figure 7-10: Percentage reduction in embodied carbon estimated for the use of timber cassette in place of insulated steel deck for each combination of scenarios modelled as part of the uncertainty assessment. Positive results only – see Figure 7-11 for negative results. Modules A-C (cradle to grave) only.

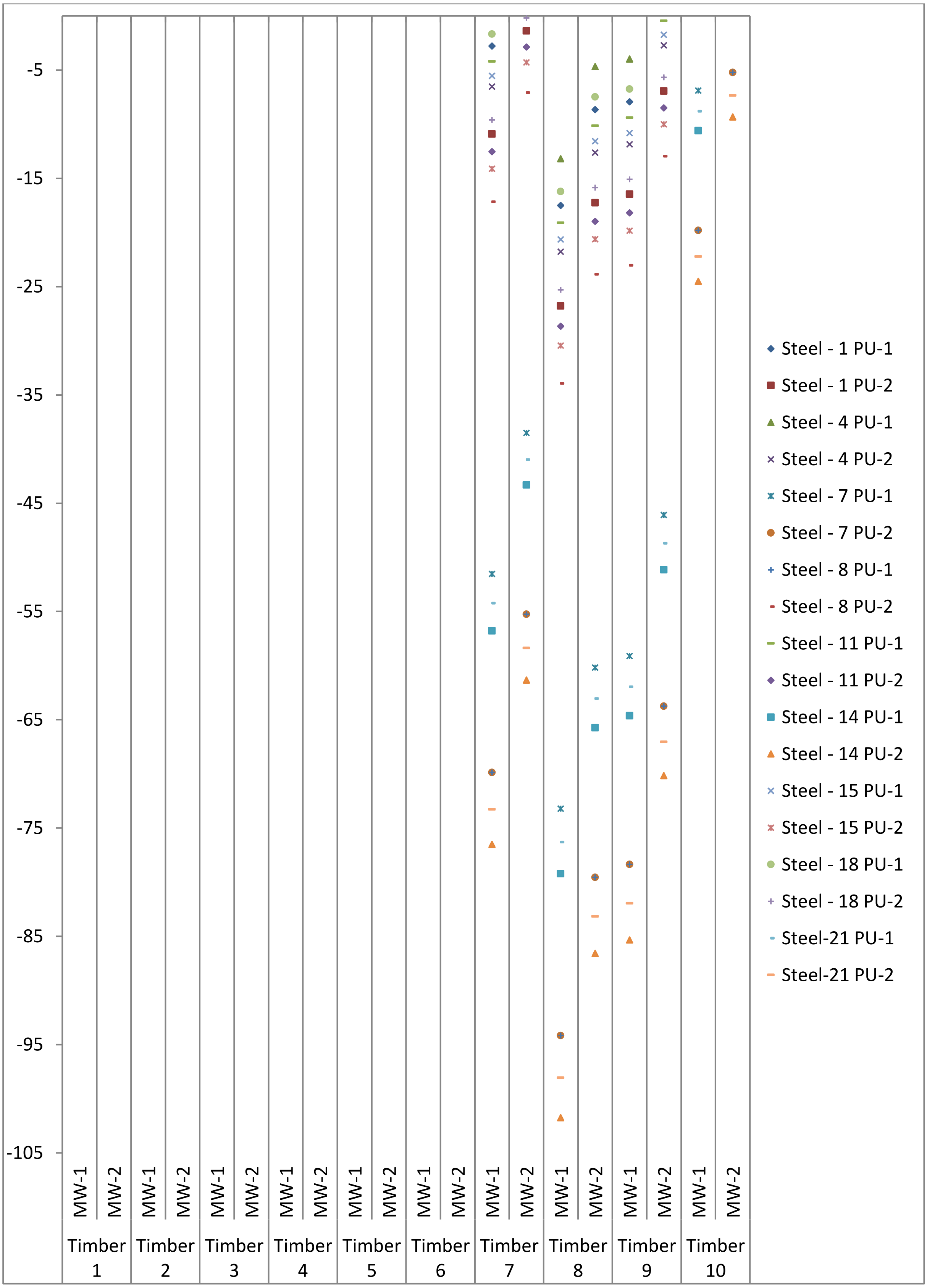


Figure 7-11: Percentage reduction in embodied carbon estimated for the use of timber cassette in place of insulated steel deck for each combination of scenarios modelled as part of the uncertainty assessment. Negative results only – see Figure 7-10 for positive results. Modules A-C (cradle to grave) only.

The results in Figure 7-10 and Figure 7-11 show that the change in embodied carbon by moving from a steel deck to timber cassette roof ranges from a reduction of some 150% in the best case scenario to an increase of around 100% in the worst case. The data shows that for the scenarios which are more favourable to the timber cassettes, the difference between the estimated savings against each of the steel scenarios becomes less distinct. This is due to the percentage savings being calculated relative to the steel deck data.

The order of the markers is different between the two charts which show percentage values in Figure 7-10 and Figure 7-11 and the absolute values in Figure 7-9 . For example, the scenario Steel-8, which represents EU BOF steel with physical allocation and the recycled content approach applied can be seen to be lower than some of the scenarios where industry average steel data have been used. This highlights the interaction between the different sources of uncertainty when comparing two composite materials.

If credit is given for sequestered carbon in the timber (Timber-1 – 5) then the timber cassette results in a reduction of embodied carbon for all scenarios when compared to the steel deck system. There is very little difference between the different end of life scenarios included, with savings estimated to be between 20% and 70% depending on the steel scenario chosen. The exception to this is for the landfill scenario with low rates of decay (Timber-1) where much of the sequestered carbon effectively remains stored in the landfill rather than being released during the 100-year assessment period. Here the savings estimated are over 100% or between about 450 and 750 tonnes CO_2e in absolute terms. The similarity between the results for scenarios Timber-2 – 5 are due to the exclusion of benefits beyond end of life (module D) from the cradle to grave boundary. Without module D, the incineration (Timber-3) and energy recovery (Timber-4) scenarios are identical, since in both cases all the carbon stored in the timber is released during combustion. Similarly, for the recycling scenario (Timber-5), the sequestered carbon is reported as an emission in order to allow the recycled product to also claim benefit from these sequestered emissions without double counting. The problem with this approach, which has been discussed in section 6.2.3, is that it incorrectly implies that carbon has been emitted to the atmosphere. Seen in the context of a comparative assessment such as is presented in this case study, the approach also penalises the user of the timber in the first life cycle. This could potentially reduce the incentive to use timber and suggests that, from the first user's perspective, there is no additional embodied carbon benefit to be achieved by prioritising recycling or reuse over other end of life processes.

The results shown here suggest that care needs to be taken when applying the methods set out in EN 15804. The requirement to maintain physical flows such as biogenic carbon could lead to undesired consequences. The uncertainty assessment approach that has been developed here highlights these important considerations. In this way it can provide decision makers with a more informed basis on which to adopt different methodological approaches and make assumptions about materials and future scenarios. The results of this case study also highlight that when estimating cradle to grave embodied carbon reductions consideration should also be given to the benefits beyond end of life (module D) of different waste treatment options. Whilst these cannot be credited to the building being assessed, under the rules of EN 15804, they nevertheless are an important factor in the selection of appropriate waste treatment methods.

7.3 Case Study 7-3: Standard Concrete vs. Low Carbon Concrete for In-Situ Floor Slab

The third of these material comparison case studies assesses how uncertainty affects the estimation of the embodied carbon savings that can be achieved by specifying concrete with a proportion of SCM to replace standard cement. Replacing cement with SCMs is commonly cited as an appropriate measure to reduce the embodied carbon impact of concrete and consequently such concretes are sometimes referred to as low carbon concrete. This term is used here to distinguish between concrete with SCM and standard concrete made with standard cement. This case study has been based on a trial of low carbon concrete carried out for Sainsbury's as part of this research.

7.3.1 Low Carbon Concrete Trials

The evidence from Sainsbury's prior work and the early analysis conducted during this research highlighted concrete as an important and significant contributor to the total embodied carbon of new supermarkets. In light of this, a trial of alternative mixes was instigated as part of this research in 2013. The purpose of the trial was to explore practical barriers and the carbon savings achievable from using SCMs as a replacement for cement in concrete for elements of the sub-structure of new supermarkets. The trials involved two Sainsbury's supermarkets constructed by the same main contractor but in different parts of the country and therefore with different concrete sub-contractors. In both cases, the trials were instigated post tender. It was therefore not possible to explore any significant structural redesign due to cost and time constraints. The scope of the trials was thus to achieve the highest proportion of cement replacement possible within the constraints of the contract and the existing concrete design. This put limits on the amount of cement replacement achievable with SCMs and also on what SCM could be supplied by the concrete sub-contractor. Gaining these first-hand insights into the practicalities of specifying low carbon concrete was a valuable outcome for Sainsbury's. The results of the trials in terms of embodied carbon savings estimated by the concrete supplier can be seen in Table 7-4. However, SCMs have been in wide use in the concrete industry for many years due to the properties that they can provide or enhance. There is a significant extant body of research on the use and effects of using SCMs to replace OPC in concrete design and so this does not form part of the scope of this thesis. The carbon benefits of SCM usage are a relatively new consideration. As has been discussed in sections 6.2.2.1 and 6.2.6.3 of the previous, the question of how to allocate emissions to SCMs, particularly PFA and GGBS, continues to be a source of controversy. This research therefore offers new insight into how this and other sources of uncertainty affect the comparison of embodied carbon for standard and low carbon concretes.

The uncertainty assessment is conducted for one of the concrete elements for which an alternative concrete mix was specified. The trials included other elements of the substructure of two supermarkets. However, since the same sources of uncertainty would be assessed in all cases, the outcomes would be comparable for each element, albeit with different absolute values.

Material quantities and concrete mix details were provided by the concrete supplier. They also provided Sainsbury's with 'carbon footprint' certificates for the low carbon concretes, which were used to estimate the carbon emissions saved by changing the concrete mix. These details are listed in Table 7-4, which shows that based on the supplier's data, just over 20% of the OPC was replaced with PFA. The GGBS mix details shown in the table were not used in the trial because the main contactor had concerns that the slower strength gain of concrete containing GGBS would impact on the programme. However, the details are included here to allow comparison of the two different SCMs. The use of PFA was estimated by the concrete supplier to achieve an embodied carbon saving for the concrete of almost 18%. The GGBS mix, which represents a 50% replacement of the cement, was estimated by the supplier to achieve just under 55% carbon saving.

Table 7-4: Details of the trial of 'low carbon concrete' at one of Sainsbury's new supermarkets built in 2013. Data provided by Cemex (2013) and Hanson

		Standard concrete	**Low carbon concrete**	
			PFA	GGBS
Volume (m^3)		2785.8	2785.8	2785.8
Mass (tonnes)		6518.8	6504.8	6504.8
Of which:				
Cement (tonnes)		936.0	732.7	468.0
Aggregates (tonnes)		5095.2	4997.7	4997.7
SCM (tonnes)		0.0	314.8	520.9
Carbon Factor (kgCO_2e/tonne)		0.148	0.122	0.067
Total embodied carbon (tCO_2e**)**		964.8	795.3	437.4
Carbon Saving	**Tonnes**	-	**169.5**	**527.4**
	Percentage	-	**17.6%**	**54.7%**

In the original design of the substructure there was no specification of SCMs to provide particular properties. It is therefore, reasonable to assume that carbon saved due to the inclusion of PFA or GGBS in the concrete mix represents an additional[8] benefit achieved through the change of specification rather than something that would have been realised without intervention.

7.3.2 Scope and Boundaries of the Assessment

This assessment is of the cradle to grave embodied carbon for the concrete only. The volume of steel reinforcement for both the standard and the low carbon concretes is assumed to be the same. The steel can therefore be excluded from the comparison of the two mixes since uncertainty in the embodied carbon of the steel has no bearing on the estimated embodied carbon saved by using SCMs as cement replacement. The energy and associated carbon emissions for construction have not been included due to a lack of available data specific to concrete. The use of SCMs may delay early strength gain (curing times) of concrete compared to 100% OPC (Hannesson et al., 2012). Nevertheless, it is not considered likely that this would result in additional carbon emissions and so omitting the construction stage of the life cycle from the comparison is not expected to have any effect on the results.

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[8] The principle of additionality is an important consideration when assessing carbon reduction or abatement measures. For a discussion and full definition of additionality see, for example (CDM Rulebook, n.d.)(CDM Rulebook, n.d.)

7.3.3 Results

In section 6.2.6, sources of scenario uncertainty affecting the carbon factor of each of the constituent materials of concrete and for concrete itself were identified. Carbon factors were derived from a range of sources to reflect each of these different scenarios. The total number of scenarios for standard and low carbon concrete is given by multiplying the scenarios for each constituent material together and then by the number of scenarios for the concrete itself. For standard concrete (4 scenarios), which comprises aggregates (10 scenarios), cement (6 scenarios) and water (no scenarios modelled), there are thus 240 different scenario combinations (4 x 10 x 6 = 240).

For low carbon concrete, two of the four cement scenarios were excluded. These were Cement-3 and Cement-4 (see Table 6-18 in section 6.2.6.3) which relate to industry average cements. These are not appropriate for assessing the cement portion of a known concrete mix such as the low carbon concretes assessed here. Since both these scenarios relate to weighted averages of all UK supplied cements (Cement-3) or cementitious materials (Cement-4), they include industry average proportions of GGBS and PFA. They are therefore only included in the assessment of standard concrete. In addition to cement, aggregates and water the low carbon concretes contain either PFA (6 scenarios) or GGBS (8 scenarios), there are therefore either 720 (PFA) or 960 (GGBS) scenarios in total for the carbon factor of low carbon concrete. Each of these scenarios represents a different combination of assumptions or methodological choices which have been identified in the expert elicitations as contributing to uncertainty in the carbon factor of the concrete and its constituent materials.

The scenarios relating to aggregates, cement and SCMs have an effect on the carbon factors for the acquisition and transport of raw materials (modules A1 and A2). The scenarios for concrete affect the carbon factors for transport to site (A4) and the end of life (C1-4 and D). The range of values for these different modules and for the cradle to grave embodied carbon (Total A-C) which arises when all the sources of scenario uncertainty are considered are plotted in Figure 7-12A-C for the standard and the low carbon concrete mixes.

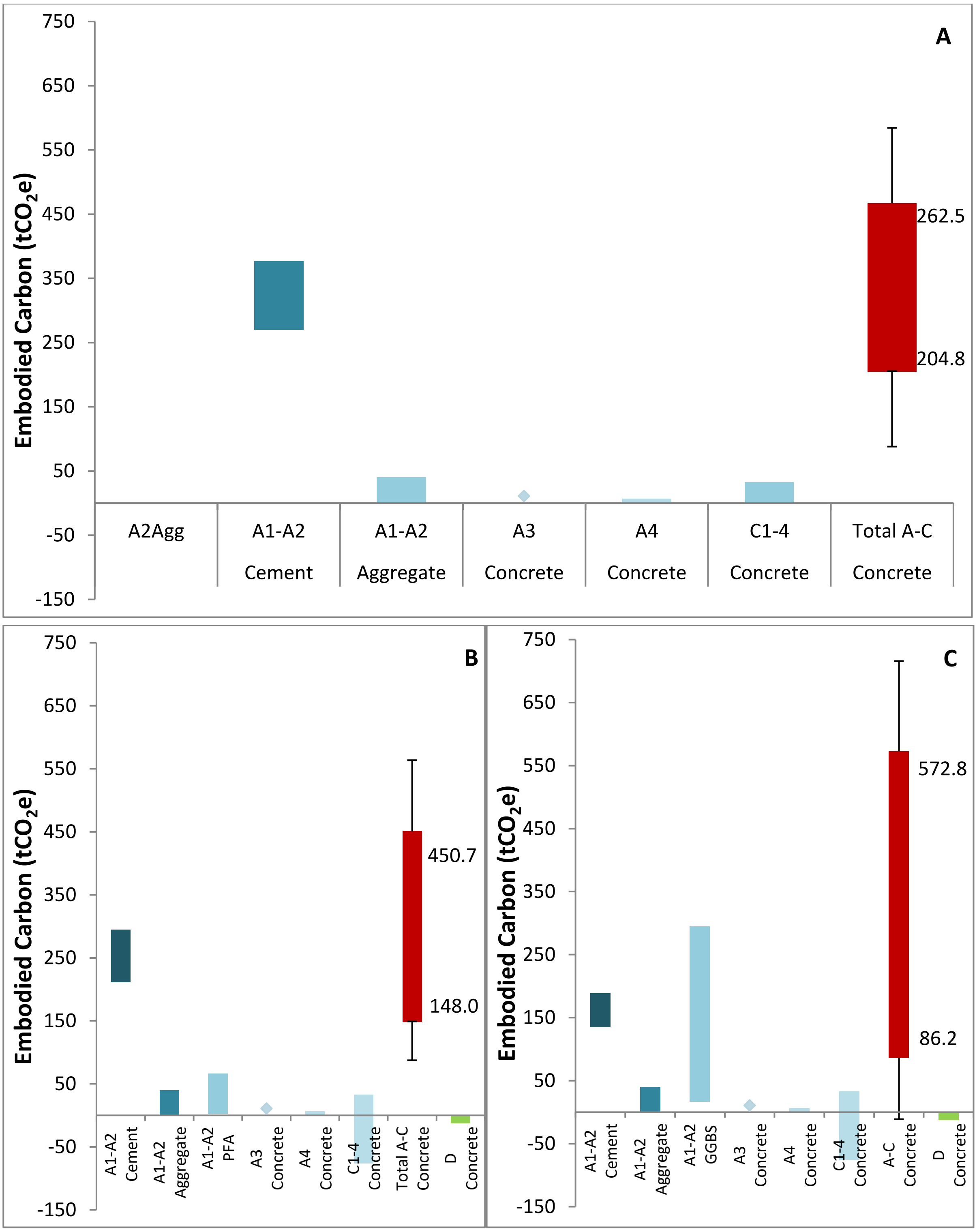


Figure 7-12: Assessment of the effects of scenario and statistical uncertainty on the embodied carbon factor of standard (A) and low carbon (B = 21.7% PFA; C = 50% GGBS) mixes of RC32/40 concrete for an in-situ poured concrete floor-slab

Notes:
The bars represent the effect of scenario uncertainty. Statistical uncertainty is represented by the error bars applied to the cradle to grave carbon factor for concrete (Total A-C). N.B. A3 is an absolute value rather than a range.
PFA = Pulverised fly ash
Life cycle modules A1-D are based on EN 15804 and are defined as follows
A1 = raw materials acquisition; A2 = raw material transport; A3 = manufacture/production; A4 = transport to construction site; C1-4 = demolition, waste transport, processing and disposal; D = Benefits beyond the end of life

The results in the figures show that there is significant overlap in the total cradle to grave carbon factors between the standard and the low carbon concretes. For the standard concrete, the effect of the scenario uncertainties identified is that the maximum possible value for the cradle to grave carbon factor (Total A-C) is more than double that of the lowest value. For PFA the maximum is three times the minimum and for the GGBS concrete, it is almost seven times greater than the minimum.

The charts also reveal which of the life cycle modules has the greatest effect on the overall uncertainty of the embodied carbon of concrete. For the standard concrete, the greatest range of uncertainty is seen in the end of life modules (C1-C4), followed by the uncertainty in the carbon factor for supply (A1-2) of cement. These two contribute 42% and 41% of the overall uncertainty range respectively. The contribution of each module relative to the total scenario uncertainty range for the cradle to grave (A-C) carbon emissions is shown in Table 7-5 for all three mixes. The benefits beyond end of life (module D) are, by definition, not included in the total cradle to grave carbon factor and so do not contribute to its overall uncertainty. The figures for module D are included to allow comparison of the effect of uncertainty on this module relative to the other modules.

Table 7-5: Contribution of uncertainty in the specified life cycle stages to overall uncertainty in the cradle to grave carbon emissions

	Standard concrete	**Low carbon concrete**	
		PFA	**GGBS**
Cement (A1-2)	41%	28%	11%
Aggregate (A1-2)	15%	13%	8%
SCM (A1-2)	-	21%	57%
Transport of concrete to site (A4)	2%	2%	1%
End of life (C1-4)	42%	36%	22%
Benefits beyond end of life (D)	*5%*	*4%*	*3%*

N.B.: Uncertainty from module D does not contribute to the total but is reported here as a percentage relative to the total to allow comparison

For both the standard and the PFA concrete, the uncertainty in the carbon emissions for supply of cement and for the end of life treatment are the most significant contributing factors to overall uncertainty in the cradle to grave carbon factor. Uncertainty in the carbon factor for supply of GGBS has the greatest effect for the GGBS concrete. This is a result of the inclusion of mass allocation as a scenario for GGBS, which leads to a carbon factor for GGBS that is higher than that of OPC. It is also due to the increased ratio of SCM to OPC this mix compared to the PFA mix. For the designated concrete mixes detailed in the UK standard BS 8500 (British Standards Institution, 2006c), GGBS can replace up to 80%

of the OPC, whereas for PFA, the limit is 35%. Based on the results of this assessment, it is therefore to be expected that in most cases, the effect of scenario uncertainty would be greater for GGBS concrete mixes those containing PFA.

7.3.3.1 Estimating the Carbon Reduction Potential of Low Carbon Concretes

In order to assess the effect of these uncertainties on the potential savings that can be achieved by replacing OPC with PFA or GGBS, it was not necessary to include all the scenarios. For example, since the aggregates in all three cases would be sourced from the same supplier, the same assumptions about the type of aggregate and the transport mode can be applied to all three mixes. This also applies to the concrete batching location, which affects the transport emissions for the concrete (A4). An argument could be made to include uncertainties relating to the end of life emissions for the concrete. Their inclusion would show how different end of life processing options might increase or reduce the estimated carbon savings. However, since the inclusion of SCMs in the concrete mix would seem unlikely to have any bearing on the choice of waste processing (mainly because at demolition it would be very difficult to establish what the concrete mix was) the scenarios relating to different end of life processes has also been excluded from the following analysis.

If this method were applied to compare concrete with a different material, for example steel such as for the structural frame of a building, it would be necessary to include these sources of scenario uncertainty excluded here. The uncertainty assessment results for the carbon factors of concrete and its constituents presented in section 6.2.6 could be used to conduct such an assessment.

An initial review of the results revealed that the effect of uncertainty about where the SCM is blended with the OPC has an almost negligible effect on the outcomes. The effect of this choice on the carbon factor for the SCM alone was shown to be only minimal in section 6.2.6.3 and when the other constituent materials are included and the end of life impacts of the concrete, this effect is reduced to less than 0.7% difference between the two blending location scenarios. This can be seen in the chart in Figure 7-13 which plots the range of carbon factors for each of the PFA scenarios.

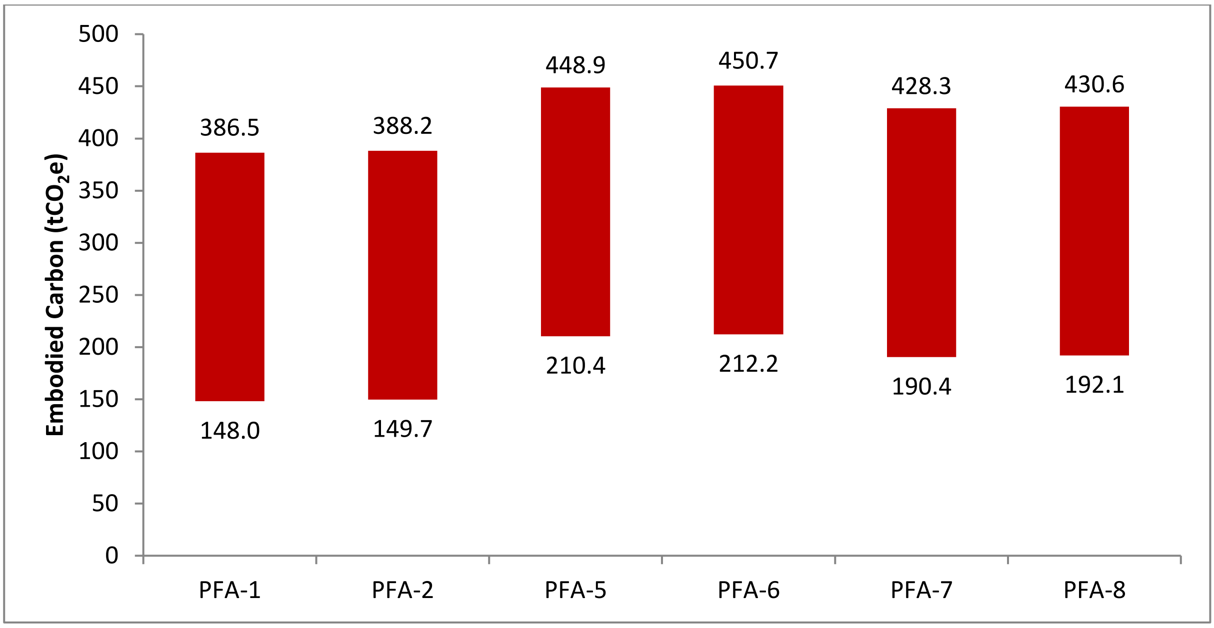


Figure 7-13: Assessment of the effects of scenario uncertainty on the embodied carbon of concrete containing PFA as a replacement for standard cement. The data represent all 1,440 scenarios for PFA and are grouped according to the sources of scenario uncertainty identified for supplementary cementitious materials. The data ranges represent the maximum and minimum values for embodied carbon based on a given set of assumptions for PFA.

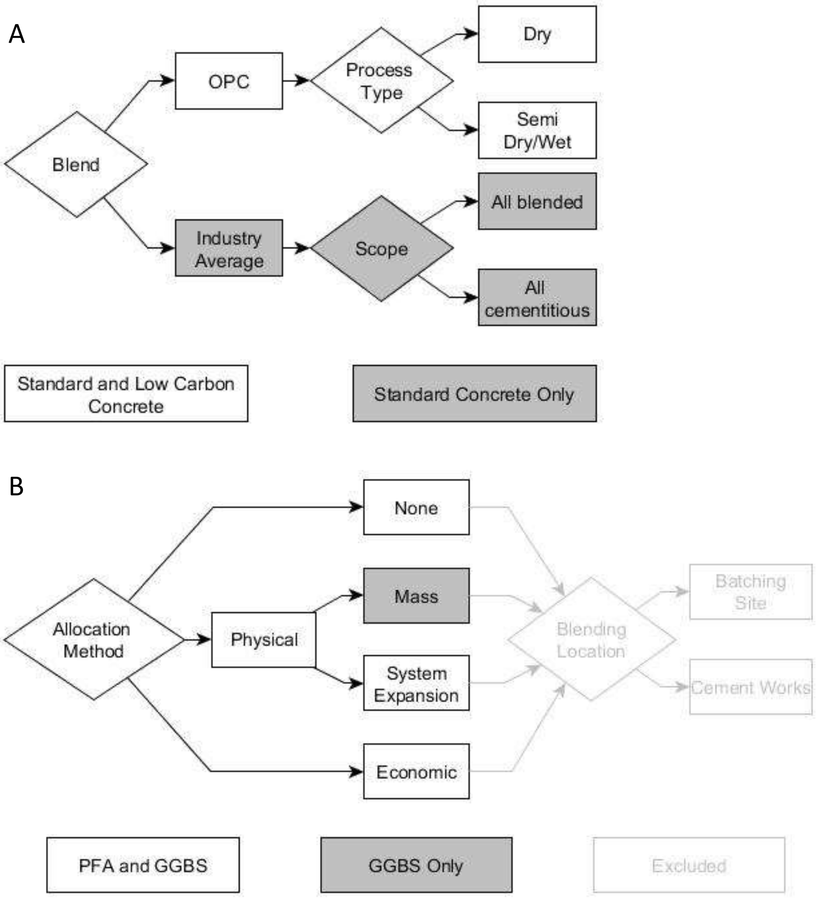
Notes:
PFA = Pulverised fly ash
PFA 1-8 illustrate the effect of relevant sources of scenario uncertainty identified in the expert elicitations detailed in section 6.2.6.
The data are for cradle to gate embodied carbon (modules A-C) with the exception of construction (module A5)

Scenario Classifications:
PFA-1 = No allocation, blended at concrete batching site
PFA-2 = No allocation, blended at cement works
PFA-5 = System expansion, blended at concrete batching site
PFA-6 = System expansion, blended at cement works
PFA-7 = Economic allocation, blended at concrete batching site
PFA-8 = Economic allocation, blended at cement works

Scenarios PFA-3 and PFA-4 would relate to mass allocation and are omitted for PFA since this is not applicable (see section 6.2.6.3.1)

Scenarios PFA-1 and PFA-2 (and 5 and 6, 7 and 8) have the same allocation method but assume a different blending location. Given that the effect of blending location is almost negligible, the subsequent results and analysis can be further simplified by omitting this source of uncertainty from the assessment. The remaining results presented for low carbon concrete therefore only include those scenarios for PFA and GGBS where blending occurs at the cement works. This was chosen since the emissions are higher, albeit only very slightly, than if blending of the SCM and OPC occurs at the batching site. It therefore represents the more conservative of the two alternatives.

The sources of scenario uncertainty included were therefore those relating to the raw material acquisition of cement and SCMs (A1). This reduces the number of scenarios for each concrete mix to four for standard concrete and six and eight for the PFA and GGBS concrete mixes respectively as shown in the figures below.



Standard Concrete: 4 Scenarios
PFA Concrete: 2 x 3 = 6 Scenarios
GGBS Concrete: 2 x 4= 8 Scenarios

Figure 7-14: Decision trees representing the sources of scenario uncertainty for cement (A) and SCMs (B) included in the comparative assessment of standard and low carbon concrete.

Since the carbon factors for industry average cements are published by the UK industry body, it can be assumed that they do not use any allocation for the SCM proportion. It is therefore somewhat unreasonable to make a comparison between low carbon concrete where allocation, of whichever kind, has been applied to the SCM and these industry average figures. For this reason, these industry average cements have only been compared to the low carbon concretes scenarios without allocation as can be seen in Figure 7-15A-B and Figure 7-16A-B.

Statistical uncertainty has not been included in the following charts on the basis that for a given building both types of concrete and their constituents are likely to come from the same supplier and so the effect of statistical uncertainty would be negated in the comparison. For example, one source of statistical uncertainty might be the efficiency of the cement production. However, cement in the standard and low carbon concrete would be produced with the same efficiency if it were sourced from the same plant at the same time.

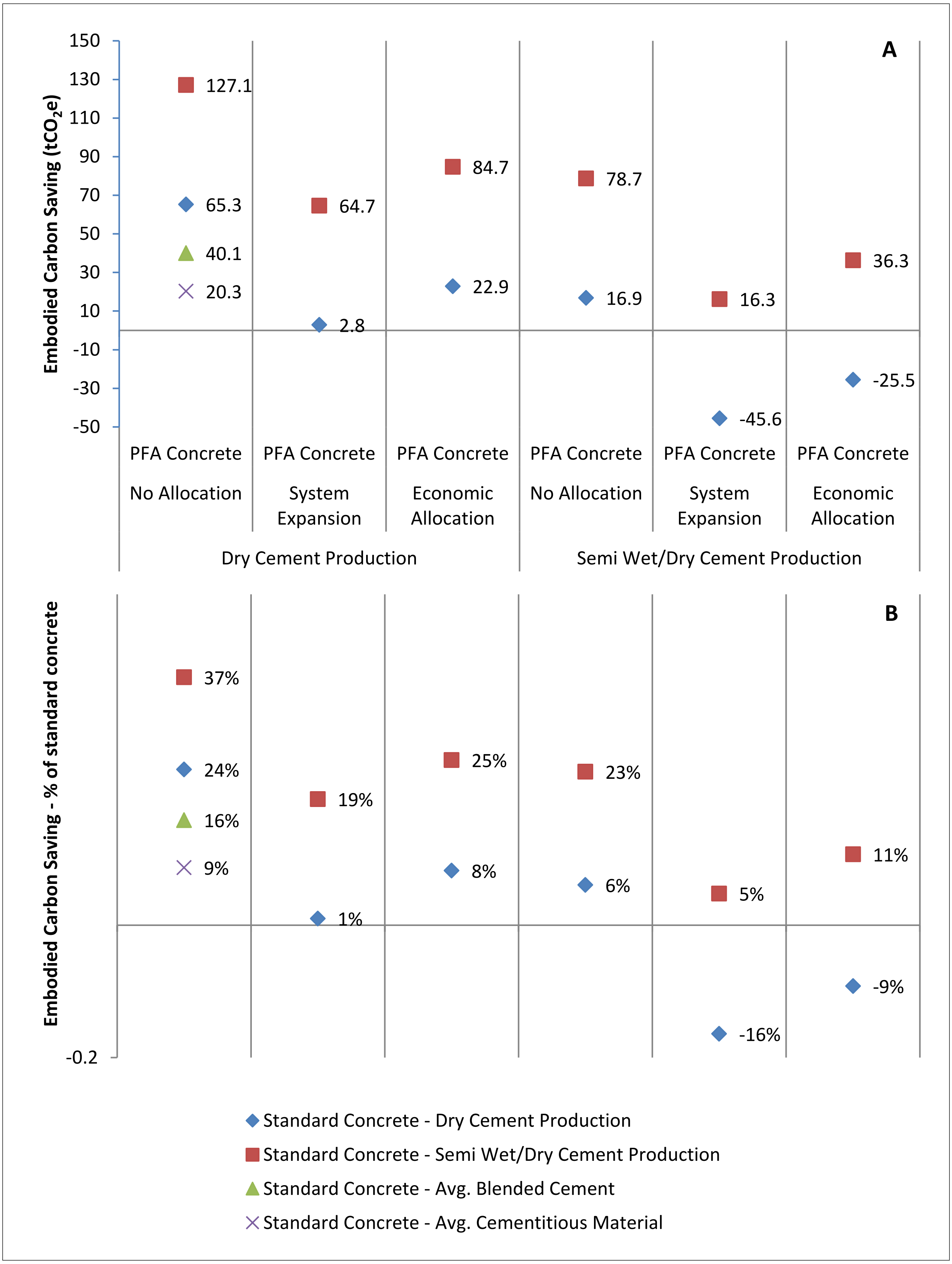


Figure 7-15: Embodied carbon reduction in absolute (A) and percentage (B) terms from replacing standard concrete with low carbon concrete (21.7% PFA) at design stage.

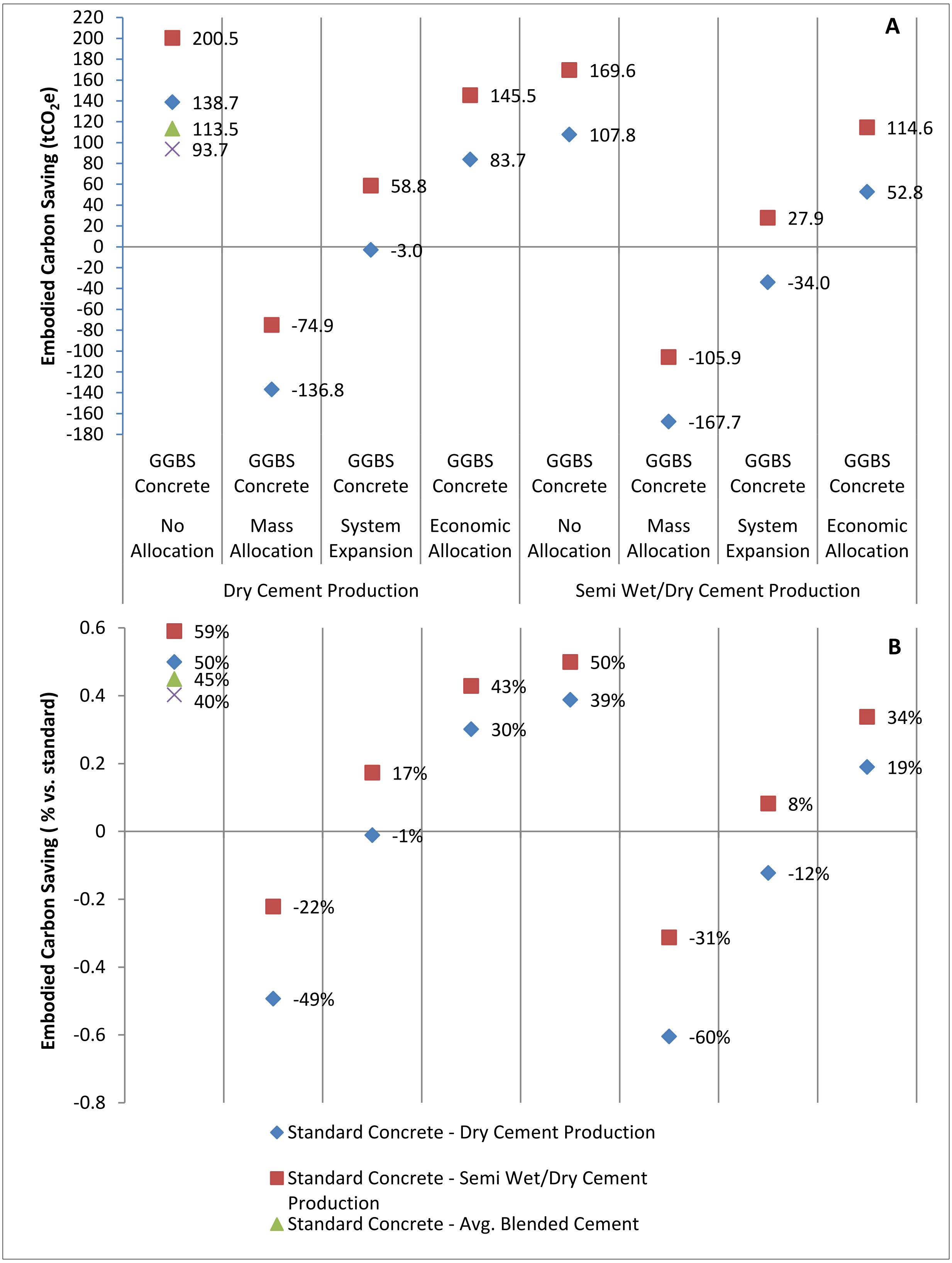


Figure 7-16: Embodied carbon reduction in absolute (A) and percentage (B) terms from replacing standard concrete with low carbon concrete (50% GGBS) at design stage.

The charts in Figure 7-15A-B and Figure 7-16A-B show that the effect on the embodied carbon of concrete of using PFA as cement replacement ranges from a 37% reduction to a 16% increase. For GGBS, where the effect of scenario uncertainty has been found to be greater, the effect ranges from a 59% saving to a 60% increase.

7.3.3.1.1 Comparing Different Allocation Methods

The difference between the system expansion method of allocation and using no allocation is of particular interest. The former is the method that is promoted and widely applied by the steel industry, where GGBS originates. The latter is the method that the cement and concrete industry bodies apply when calculating the carbon factor of GGBS and PFA used in concrete. If no allocation is applied, then replacing 20% of the OPC with PFA is seen to reduce the embodied carbon of the concrete in six out of eight of the possible scenarios. The maximum possible reduction (37.5%) is seen when comparing PFA concrete using dry-produced cement vs. standard concrete using semi wet/dry cement. The comparison of scenarios where the same cement production type is assumed for both the standard and the low carbon concrete is perhaps more reasonable, given that the source of the cement would be the same for both. In these cases, the savings are around 23% if no allocation is used but are less than 5% if system expansion is applied.

For GGBS, to which these two differing allocation approaches are routinely applied by the two sectors that produce and use the material, the contrast is starker. If no allocation is used, the embodied carbon saving from the replacement of 50% OPC with GGBS is estimated to be 50%. Yet if system expansion is applied, this decreases to around 8% when assuming semi wet/dry production and -1% (or a 1% increase) for dry-produced cement.

These results are unsurprising considering that the system expansion approach allocates emissions to the co-product (PFA or GGBS in this case study) equivalent to the material that the co-product substitutes. Thus, using system expansion, GGBS and PFA are deemed to have emissions equivalent to those of OPC, albeit with a slight adjustment to account for the lower binding capacity of the two SCMs. Therefore, if the system expansion method is adopted, there is effectively no carbon benefit from using either PFA or GGBS. Yet despite the important effect of this methodological choice, system expansion has often been overlooked in previous work assessing different allocation methods for SCMs (Grist et al., 2015; Darby, 2014; Chen et al., 2010).

The effect of economic allocation is also to reduce the estimated savings, albeit less significantly than the system expansion method. The use of mass allocation for GGBS leads to significantly higher embodied carbon for the GGBS concrete than standard concrete.

7.3.3.1.2 Comparison of SMCs with OPC or Industry Average Cement

Importantly, if the embodied carbon of the standard concrete is calculated based on industry average cement (either including or excluding unblended SCMs), the estimated saving from the use of SCMs is significantly decreased. For PFA without allocation, the estimated savings reduce from 23% (comparing like for like cement production types) down to 16% if the standard concrete is based on average blended cements or 9% for the average of all cementitious materials. For GGBS, the equivalent figures are 50% saving compared to 100% OPC versus 45% or 40% savings compared to the two industry average figures.

It could be argued that industry average figures for cement represent standard practice and therefore savings should be evaluated against these. The savings estimates for the low carbon concrete trials provided to Sainsbury's by the concrete supplier were based on a comparison with 100% PFA. The same is true of the savings estimates in the previous whole-building studies undertaken for Sainsbury's (dCarbon8, 2007, 2008, 2009, 2010; Deloitte, 2010) and also those reported in the literature reviewed for this research (e.g. Darby, 2014) .

7.4 Conclusions

The use of alternative materials to reduce embodied carbon is a widely accepted approach. However, there is significant uncertainty affecting carbon factors of different materials and this leads to uncertainty as to how much carbon can be saved through the use of alternative materials. This research shows that the combined effect of uncertainties affecting the carbon factors of both the standard material and the proposed alternative can be so great that either material could have the lower embodied carbon if different assumptions or methods are used. This was found to be the case even for materials that are widely viewed as low carbon alternatives such as timber and cement replacements (SCMs).

Care should always be taken when evaluating potential savings to ensure that assumptions and methods are reasonable and justifiable. Uncertainty assessment should be standard practice for such comparisons to ensure uncertainty and the risks it introduces are understood by designers and decision makers.

8 Discussion of the thesis results and their implications

8.1 Introduction and Summary of Key Findings

The research aim was to propose and demonstrate a new approach to estimating embodied carbon of supermarket buildings during the design stage, taking account of uncertainty and evaluating how the approach may support decisions aimed at reducing carbon emissions in construction. In support of this aim six objectives were identified (see below) and the work presented in chapters 2-7 of this thesis fulfils the first five of these as summarised in Table 8-1. Finally, the sixth objective is discussed here and the research methods and outcomes are evaluated. Some important implications of the research are reviewed and discussed, including implications for Sainsbury's approach to addressing embodied carbon in the design of future supermarkets.

The aim and objectives identified in chapter 1 were as follows:

Objectives:

1. Identify suitable sources of data for use in the estimation of embodied carbon in supermarket construction and evaluate their usefulness for Sainsbury's.
2. Evaluate the potential to automatically generate material quantities data that are appropriate for embodied carbon assessments using Sainsbury's BIM models, and to make recommendations for their improvement.
3. Develop and demonstrate a new approach for estimating embodied carbon of supermarket construction on the basis of 1 and 2 above.
4. Investigate the nature and potential impact of uncertainty in estimating embodied carbon, and evaluate current approaches for assessing it.
5. Develop and demonstrate an approach to incorporating uncertainty assessment into the estimation of embodied carbon at 3 above to show the effect uncertainty can have on design decisions to reduce embodied carbon.
6. Examine how embodied carbon assessment results produced using this new approach can support Sainsbury's aim of reducing its climate change impacts.

The key findings from the research are summarised in Table 8-1 with reference to chapter where they are presented and the specific objectives that they address.

Table 8-1: Summary of key outcomes from the research presented in the preceding chapters and their relevance to research objectives 1-5

Objective	Key Findings	
1	Six main types of carbon factor data source were identified.	Chapter 2
	Evidence was identified to suggest EPD are rapidly becoming the most widely used and accepted source of embodied carbon factor data.	Chapter 2
	The six carbon factor sources were evaluated for data quality and ranked in order of preference for use in the analyses conducted. EPD ranked highest for data quality.	Chapter 6
2	A method was developed and demonstrated to codify material quantities and carbon factors using a standardised set of material categories in order to semi-automate the process of linking these data together.	Chapter 4
	The main limitations of Sainsbury's BIM models were identified and described including: • misalignment between geometry for multi-file models, • incomplete modelling at building level, • incomplete modelling at object or element level, • missing or simplified geometry, • unspecified materials, • incorrectly allocated objects	Chapter 4
3	Three supermarket building case studies were modelled using the method developed in support of objective 2 and the carbon data priorities established in support of objective 1	Chapter 4
	Cradle to gate emissions were identified as having the largest impact, typically over 50% of the total cradle to grave embodied carbon.	Chapter 4
	Refurbishment impacts also make up a large proportion of the total, particularly when shelving and chilled cabinets are included.	Chapter 4

4	Through systematic literature review, 18 sources of uncertainty relevant to embodied carbon factors of construction products were identified.	Chapter 2
	Categorising these sources according to a commonly used uncertainty typology revealed that there are two distinct groups, scenario uncertainties and statistical uncertainties	Chapter 5
	The techniques most commonly applied in assessments of buildings focus on statistical uncertainty and are not well suited to accounting for scenario uncertainty. Therefore, the effect of these uncertainties on results is not well understood	Chapters 2 and 5
5	A novel approach for assessing the effects of scenario and statistical uncertainties on embodied carbon assessments was developed and applied to three case-studies.	Chapter 5
	This method was applied to assess the effects of relevant scenario and statistical uncertainties on the embodied carbon factors of eight materials commonly used in supermarkets construction.	Chapter 6
	The effects of the assessed uncertainties were modelled for three material comparison case studies. Each case study involved a comparative embodied carbon assessments of a typical and an alternative low carbon material for a particular building element of a supermarket	Chapter 7

8.2 Discussion of Key Outcomes

8.2.1 Embodied Carbon in Supermarkets

The results of the building case studies presented in Chapter 4 showed that there are common elements which contribute significantly to the embodied carbon of the supermarkets assessed. The cradle to gate embodied carbon of the building materials is the major contributor in all three building case studies. This is consistent with prior assessments of a number of different types of non-domestic building (Darby, 2014; Kua & Wong, 2012; Kofoworola & Gheewala, 2009; Xing, Xu, & Jun, 2008).

The main contributors to this life cycle stage for the case study buildings are the concrete in the sub-structure and the steel for the structural frame. This suggests that efforts to reduce the embodied carbon in supermarkets should focus first on these two materials. The external works were not included in the case studies because the material quantities were not available from the BIM model. Their inclusion would reduce the relative contributions of concrete and steel, but in previous analyses commissioned for Sainsbury's where external works were included, these two materials together still accounted for the largest proportion of the total embodied carbon (Deloitte, 2010).

The embodied carbon of refurbishments during the use phase of the building is another major contributor to the total, particularly when shelving and chilled display cabinets are included. The regular refurbishment cycles that supermarkets typically adopt are an important driver of these impacts. In the assessments conducted here, it has been assumed that all the internal fit-out items are replaced every 10 years. This assumption is based on informal discussions and observations made during the course of the research. Applying the average service life of supermarkets, identified in this research to be around 25 years (Richardson et al., 2014), means there are two refurbishments carried out during the building's life. The high volumes of sheet steel used in the shelving and the chilled cabinets result in approximately 30kg of steel per square meter of gross internal area in the initial fit out, rising to 90kg/m2 when the subsequent refurbishments are included. This is significantly higher than the mass of steel in the structural frame (for the steel framed buildings assessed) which was around 37 kg/m^2. The high embodied carbon of sheet steel relative to steel section (Darby, 2014; Hammond & Jones, 2011) contribute to the importance of this life cycle stage.

For the 60k Model store assessed in Case Study 4-1 in Chapter 4, the fit out items, were found to be responsible for over 4,300 tCO$_2$e over the 25 year service life when accounting for two refurbishments in that period. This represented over 50% of the total embodied carbon of the building. Applying simple sensitivity analysis to the results showed that each additional refurbishment resulted in a further 1,300 tonnes of embodied carbon for the building. So if the service life of the fit out items could be extended to 15 years instead of 10, meaning only one refurbishment in 25 years, the embodied carbon of the building is reduced by over 15%. Therefore, assumptions about service life are particularly important when assessing the embodied carbon of internal fit-out items. It has been shown here to be particularly relevant to supermarkets because of the volumes of sheet steel, a carbon intensive material, used in the store fit out, particularly shelving. The literature review showed that in previously published studies of the embodied carbon of buildings a nominal service life of 50 years has often been adopted. Where justification for this is given, it is typically based on nominal service life lengths set out in design codes (e.g. Darby, 2014). This approach is not deemed to be appropriate for supermarkets where the evidence from UK data shows that less than 2% of supermarkets sampled fall into this age bracket (Richardson et al., 2014). These data support the evidence of previous studies (Aye et al., 2012; Aktas & Bilec, 2012; O'Connor, 2004) that commercial and market considerations, rather than technical durability, are the main determinants of building service life in commercial and retail sectors. The approach adopted here, of determining typical building service life length based on empirical data for the actual service lives of buildings, provides a more realistic basis for evaluating embodied carbon. Moreover, the use of empirically determined rather than nominally specified service life in the assessment of environmental impacts highlights the important effect that service life has on the results of such studies.

For Sainsbury’s and other supermarket businesses, the results of this research raise an important question as to the environmental sustainability of current practices regarding supermarket service life. Extending the service life of buildings and building components can both reduce their life cycle environmental impacts and save capital costs. This and other embodied carbon mitigation strategies are discussed further in the following section.

8.2.2 Potential Relevant Embodied Carbon Reduction Strategies

For Sainsbury’s an important driver for conducting embodied carbon assessments is to evaluate opportunities to reduce embodied carbon. This is reflected in the final research objective and in order to fulfil this objective, potential strategies for reducing embodied carbon are discussed and evaluated in light of the research outcomes. Pomponi and Moncaster (2016) identified 17 different methods of embodied carbon reduction or mitigation that are commonly proposed in the literature. These approaches are discussed here and their relevance to supermarket construction is evaluated in light of the outcomes of this research. Of the 17 mitigation strategies identified in the original study, eight have been selected for discussion here. The mitigation strategies included in this discussion are those which could reasonably be considered during the early design stages of a project and could be objectively defined and evaluated (discussed further below):

- Use of materials with lower embodied carbon
- Reduction, re-use and recovery of high embodied carbon materials
- Inclusion of waste, by-products, into building materials
- Increased use of local materials
- More efficient construction processes/techniques
- Extending the building's life
- Increased use of prefabricated elements/off-site manufacturing

(Pomponi & Moncaster, 2016, p. 690)

Of the ten mitigation strategies excluded, six are only relevant on a macro or industry scale or else could only be considered during initial feasibility assessment before a site has been chosen. These are national policy, sectoral policy, carbon trading or taxes, carbon capture and storage, grid decarbonisation, refurbishment instead of new-build. Three of the strategies can only be subjectively evaluated and, it is argued here, would not directly lead to embodied carbon savings except through increased implementation of some of the other strategies listed. These are the use of tools, methods and methodologies to calculate embodied carbon, use of better design, and raising awareness of embodied carbon amongst built environment professionals. The last mitigation strategy omitted from the discussion here, demolition and rebuild, is not considered to have any embodied carbon benefit. Pomponi and Moncaster cite only two examples of studies that propose this approach and acknowledge that the potential benefit is in predicted operational emissions reductions, realised in spite of the 'embodied carbon costs' (2016, p. 694).

8.2.2.1 Using Materials with Lower Embodied Carbon

The uncertainty assessments described and discussed in the material comparison case studies in Chapter 7 compare the use of typical materials used in supermarket construction with alternatives that are widely viewed as having lower embodied carbon. The results suggest that due to uncertainties in the embodied carbon factors for both the typical materials and the alternatives, the use of these alternative materials may not always lead to the desired outcome of reduced emissions. This is discussed further in section 8.2.5 below.

8.2.2.2 Reduction, Re-Use and Recovery of High Embodied Carbon Materials

This mitigation strategy would seem particularly pertinent to supermarkets based on the analysis from Chapter 4. Consistent with prior studies, steel and concrete were found to have the greatest contribution to overall embodied carbon due to the high volumes used, and the relatively high embodied carbon of the materials (in the case of concrete it is the cement which has the high embodied carbon). The main reduction strategy described and discussed by Pomponi and Moncaster is that of design optimisation. In other words, ensuring only the minimum material necessary is used. Evidence suggests this can be applied to both concrete foundations (Basbagill et al., 2013) and steel structures (Moynihan & Allwood, 2014)

Sainsbury's conducts internal cost review processes, which are continuously applied, with cost reduction targets set each year. It therefore seems likely that some inefficiencies in the standard designs will have already been removed in order to reduce capital expenditure on new buildings. Where these cost reduction initiatives result in reduced use of material to enclose the same amount of space, it is likely that the embodied carbon intensity of the building ($kgCO_2e/m^2$) will have been reduced. Whilst cost reductions can be achieved by other means than reducing material use (e.g. sourcing cheaper alternatives or achieving reductions in labour) it is understood from discussions with Sainsbury's staff that some reduction in material quantities has been achieved. For example, the standard thickness of floor slabs for new stores has been reduced as a result of this initiative, as has the amount of masonry that is used. Attempts to obtain details of these reductions were made but no records of the total quantities of materials saved have been kept by Sainsbury's. Nor were adequate details available from which estimates of total material reductions could be made such as when exactly these changes took effect or the number of buildings that were affected by the changes.

With respect to reducing the amount of steel used, a review of industry benchmarks suggests that buildings of this type typically have more efficient structural designs than other steel framed buildings. The steel industry website SteelConstuction.info provides estimates of typical steel frame weights for different types of building. The website states that steel weights for low-eaves, long span buildings are 'about 30-40kg/m² overall of GIFA [gross internal floor area]' (SteelConstruction.info, 2017). These values are significantly lower than the estimates for other types of steel frame buildings which are 50-60kg/m2 and 75-90kg/m2 for low-rise, short-span and high-rise, longer-span buildings, respectively. The steel weights for the 60k Model store, based on the quantities taken from the BIM model, are around 37 kg/m^2. This suggests there may be some scope to reduce the overall steel weight by optimising the design. However, this is not expected to be significant given that these types of buildings are already some of the most efficient in terms of steel use per square meter. To test this, the quantity of steel for the frame was reduced to an amount equivalent to 30kg/m^2. This was found to reduce the embodied carbon of the building by less than 2%. The small effect of this change despite the importance of steel overall is due to the large quantity of steel in the fit out. The shelving alone, excluding chilled cabinets, contributes around 30kg/m^2 when initially installed and is then replaced twice over the assumed service life of the building, giving a total of 90 kg/m^2. For the Thanet store, the steel weights per square meter of GIA were significantly higher (106 kg/m2). However, this is due to the store being essentially a two storey structure with only one internal floor. If the carpark were included in the measured area, the mass of steel per square meter would be approximately halved. This is still high compared to the 60k Model and shows that this configuration is not an efficient structural form.

Within this mitigation strategy, the authors also include the use of supplementary cementitious materials (SCMs) as a replacement for Portland cement (OPC). This measure has been explicitly assessed in the material comparison case studies in Chapter 7. Here it was shown that there is significant uncertainty in the embodied carbon factor of two important SCMs, GGBS and PFA, and consequently in the amount of carbon reduction that can be achieved through their use. This is discussed in more detail later in this chapter in section 8.2.5.

8.2.2.3 Inclusion of Waste or By-Products into Building Materials

The use of SCMs, which are co-products (or by-products) of other processes was assessed in this research, as has been mentioned above. The examples of this mitigation strategy cited by Pomponi and

Moncaster are less common substitutions, such as the use of recycled polyethylene terephthalate (PET) from plastic bottles as a feedstock for making insulation (Intini & Kühtz, 2011). Given the dominance of concrete and steel in the total embodied carbon of supermarkets, such initiatives would, individually, have only a relatively small overall impact. The study by Intini and Kühtz, cited above, claims reduction of up to 46% of the embodied carbon of insulation could be achieved. However, this is based on a comparison with 100% virgin PET insulation. This is a significant proportion, and if such levels of reduction could be achieved for a number of building elements, then in combination, the effect could be a notable reduction in the building's embodied carbon. Clearly such initiatives have a role to play in an holistic embodied carbon reduction strategy for supermarkets. However, the results of this research show that due to uncertainty in the carbon factors of materials, caution must be applied when evaluating any potential claims about the level of reduction that can be achieved. The uncertainty assessment in case study 7-3 (section 7.3) of the comparison of standard and low-carbon concrete has highlighted the importance of the baseline that is selected for making such comparative assertions. The embodied carbon saving for the low-carbon concrete was found to be significantly reduced when the baseline was changed from 100% OPC concrete to a concrete based on industry average blended cements. The principle of additionality, which underpins international carbon abatement initiatives such as the Clean Development Mechanism (CDM Rulebook, n.d.), is equally valid in the context of smaller scale emissions reductions such as those considered here. This principle requires that estimates of carbon savings achieved by a specific initiative only include benefits that are additional to, or over and above, what would be achieved if the initiative was not undertaken. Calculating emissions reductions against an unrealistic baseline leads to overly optimistic results and should be avoided.

8.2.2.4 Increased Use of Local Materials

The transport emissions for materials from the production location to the construction site (Module A4) and construction stage emissions (Module A5) were found to contribute between 1-4% and 5-10% of the total cradle to grave emissions respectively (see Figure 4-9, Figure 4-13, and Figure 4-16 from page 93 onwards). Thus reductions in the embodied carbon of either of these stages would only have a relatively small effect on the overall embodied carbon of the building. The uncertainty assessments of carbon factors presented in Chapter 6, particularly the one conducted for steel (section 6.2.2), showed that different assumptions about the source of raw materials have a much less significant effect than other assumptions identified as introducing scenario uncertainty. Similarly, the source of raw materials for production of PU insulation was estimated to have a relatively very small effect on the material's cradle to grave embodied carbon factor (see section 6.2.5). The evidence suggests that, whilst local sourcing may have a carbon benefit, this must be considered in conjunction with the other life cycle stages.

The case study assessments in Chapters 4 (building case studies) and 7 (material comparison case studies) were carried out using data from the design stages of each building and specific product and materials suppliers, and hence transport routes, were taken to be unknown. Therefore transport emissions were assessed based on average road freight statistics for the UK. Other studies have also adopted this approach (e.g. Darby, 2014) and similar averaged distances are used in a number of EPDs or carbon footprints of products for transport at different stages of the lifecycle (Modules A2, A4 and C2) (e.g. Institut Bauen und Umwelt e.V., 2013; British Gypsum, 2013; Wood for Good, 2013b). However, the validity of such statistics for specific products is, with a few exceptions, not known. For concrete and steel, there are industry specific data available (British Construction Steelwork Association & Steel Construction Institute, 2014; Mineral Products Association, 2013). Comparison of these figures against the national averages shows that ready mixed concrete has much lower typical transport distances than the average for mineral products. However industry specific data for steel and pre-cast concrete are higher than the averages for the respective material categories. These examples suggest that the increased availability of data on the typical transport emissions of specific construction materials would be advantageous for making more robust estimates at design stage. The uncertainty associated with transport distances is reduced once specific product suppliers are known and transport distances can be more accurately estimated.

8.2.2.5 More Efficient Construction Processes/Techniques

The carbon emissions for the construction stage were estimated to be less than 10% of the building's total cradle to gate emissions for all the building case studies. However, data for this stage are not widely available in EPDs or other public data sets. Where EPDs for a specific product or material included this life cycle stage (module A5), these data were used. Elsewhere, carbon emissions for this stage were estimated as a proportion of the cradle to gate emissions for each material. This was based on evidence from prior assessments carried out for Sainsbury's (dCarbon8, 2007, p. 8, 2008, p. 8, 2009, 2010, p. 8). Other studies have shown similar results for this life cycle stage, and therefore the emissions reduction potential through increased efficiency is expected to be a relatively small percentage of the total embodied carbon of the building. Moreover, without accurate data to establish a baseline, the impact of any efficiency initiatives or improvements is very difficult to establish.

In the past, Sainsbury's employed a company to operate a system for monitoring the energy use on sites. However, this was discontinued part way through the research. The reason for this was not documented by Sainsbury's, however, samples of the data recorded for a number of buildings were obtained and were found to be inadequate for the purposes of estimating total carbon emissions for module A5. Firstly, only electricity and water consumption were logged, with no records kept of fuel use for plant and vehicles. Secondly it was found that readings were highly infrequent with many gaps and anomalies. If Sainsbury’s are to reduce their emissions for this lifecycle stage, they must first ensure that adequate data capture systems are established for all energy use on sites. Improved availability of data for the construction phase of different building types would help organisations such as Sainsbury’s and its contractors to benchmark their performance in this area.

The lack of data in EPD for this stage of the life cycle may be symptomatic of the fact that the product manufacturers, who typically produce EPDs, are not responsible for these emissions. These organisations are unlikely to have direct access to primary data for assessing these emissions. Such data, where available, is also expected to be highly aggregated, with records most likely kept for an entire construction site. Thus the approach of the EPD system, to include this stage of the life cycle is somewhat impractical. There is therefore little reason to expect that the increasing availability of EPDs generally will make a significant difference to the data availability for this life cycle stage in particular.

8.2.2.6 Extending the Building's Life

Extending building service life does not directly reduce the embodied carbon. Indeed, for supermarkets extending the service life may increase the total embodied carbon. A longer life may mean more refurbishments and hence increased emissions. However, the carbon emissions for the initial life cycle stages up to and including construction, are amortised, or accounted for over a longer period, if the building service life is extended. Building service life has been shown to be highly variable for supermarkets. Commonly applied assumptions based on the nominal design life of buildings from structural building codes have been shown to be inappropriate for supermarkets. Non-technical considerations such as market conditions, customer and competitor activity, and aesthetics appear to be more important drivers of service life than durability. The available data for UK supermarkets suggests that service lives are typically relatively short compared to standard structural design life. This is therefore an important issue for companies like Sainsbury’s to consider. The demolition of buildings that are less than 25 years old is not an efficient use of material resources and greater emphasis could be placed on maximising the actual service life achieved. Designing for future flexibility is one approach that could be more widely adopted and might help to prevent the need for such early demolitions. If buildings are designed to allow relatively straightforward expansion or sub-division, the likelihood that non-technical factors such as those listed above would necessitate demolition may be greatly reduced. Designing for deconstruction instead of demolition is another approach which can help to ensure efficient use of resources in the long term (Densley Tingley, 2013)

8.2.2.7 Increased Use of Prefabricated Elements/Off-Site Manufacturing

This approach to construction has been proposed as a means of reducing embodied carbon on the basis that the controlled environment of a factory allows for greater resource efficiency and reduced waste (Hong et al., 2016). The evidence in the literature is that this is not always the case. In some examples, reductions in embodied energy or carbon are only realised when considering multiple lifecycles for the same component. This assumes that the prefabricated components can be removed and reused at the end of life (Aye et al., 2012). Such results suggest that improvements in production efficiency alone are not significant enough to make prefabrication more favourable in embodied carbon terms than traditional on-site construction methods. A full embodied carbon assessment of such initiatives would be required to determine whether and how savings can be achieved. The tool developed and demonstrated in this research could be used to undertake such an analysis provided the embodied carbon data for prefabricated components is available. An uncertainty assessment such as has been demonstrated in chapters 5-7 would be important to identify and test the effect of different assumptions on the comparison of standard and off-site construction techniques.

8.2.3 Expert judgement of the Data Quality of Typical Sources Of Carbon Factor Data

The availability of carbon factor data with which to conduct an embodied carbon assessment has been a limitation of the method and is one of the causes of the apparent lack of comparability between studies. In order to assess the embodied carbon of a whole building, researchers have often made use of carbon factors from a number of different sources (e.g. Darby, 2014; Hammond & Jones, 2008). In some cases, multiple sources of data for the same or similar materials are available. But there can be a large differences between the carbon factor values from different sources for a given material (Dixit et al., 2010).

Six commonly cited sources of carbon factors for construction materials and products were identified in the literature. For the cases where several different carbon factors were available from different sources for the same material, a means of prioritising their selection was established. Following the data quality (or pedigree) matrix approach, first proposed by Funtowicz and Ravetz (1990, 1993), a set of data quality indicators was defined (see Table 5-1 on page 124). Ten experts, selected for their knowledge and experience in the field of embodied carbon and LCA of buildings or construction materials, were then asked to evaluate the six sources of carbon factor data against these criteria. The six sources, in descending order of data quality score are shown in Table 8-2 (for the full results and scores see Figure 6-1 and Table 6-2 on page 138)

Table 8-2: Sources of carbon factors ranked according to the data quality scores elicited from ten experts.

Rank	Source
1	EPD (EN 15804 compliant)
2	Factor from commercial LCA database
3	PAS 2050 compliant carbon footprint
4	Industry data
5	Government data
6	Factor derived/aggregated from literature

EPDs scored highest for data quality in this assessment and this result lends support to evidence in the literature which suggests EPDs are likely to become the primary source of carbon data in future embodied carbon assessments. However, despite increasing numbers of EPDs being published, they are still not available for all materials. So in this research, a range of different sources were used, with priority given to those with a higher ranking. In some cases, it was necessary to combine different sources of data in order to establish a carbon factor for all the life cycle stages for a given material. In other cases it was necessary to use data from the Inventory of Carbon and Energy (Hammond & Jones, 2011) which is also based on a wide range of different literature sources. Carbon factors derived from the literature in this way received the lowest data quality score of the six sources evaluated.

For all the six sources, the lowest scores were given for data validation, which was one of the four data quality criteria assessed. This suggests improved validation and/or clearer reporting of existing validation should be a priority for all sources of carbon factors, but particularly for EPDs due to their predicted wider use and the increasing numbers being published.

8.2.4 Different Levels of Uncertainty Affecting Embodied Carbon Data

The analysis has shown that the uncertainties which affect the embodied carbon factors of materials can be broadly categorised as having two different levels. The first are statistical uncertainties, those which can be characterised quantitatively using statistical techniques. The second are those uncertainties where different alternatives can be identified but which cannot be meaningfully represented by statistical ranges or distributions. Of the eighteen different sources of uncertainty (see Table 2-4 on page 40), ten were identified as causing scenario level uncertainty. These terms are based on Walker et al.'s (2003) conceptual framework of uncertainty as having three dimensions, which is explained in detail in section 2.7.1 of the literature review. According to Walker et al., uncertainties can be characterised by their level, but also by their location and nature. Seven out of ten of the uncertainties identified as scenario level were ‘located’ in the model context. In other words they are caused by methodological choices or assumptions made in the estimation of embodied carbon factors.

The analyses in Chapter 6 of this thesis have shown that, based on the expert elicitations conducted, sources of scenario uncertainty have a greater effect on the carbon factors of the materials assessed than sources of statistical uncertainty. For steel, the choice of method for accounting for recycling and the level of data aggregation were both found to change the carbon factor by up to around 40%, whilst estimates of statistical uncertainty elicited from the participating experts suggested that the carbon factor could vary within the range of -15% to +30%. For timber, the methodological choice of whether to include sequestered carbon changes the carbon factor by some 60%, whereas statistical uncertainties were estimated by the experts to produce a range of +/-20%.

These uncertainty ranges are not insignificant and are a key reason why there is such variability and a perceived lack of comparability in the results of different embodied carbon assessments of buildings and construction products (Darby, 2014; Moncaster & Song, 2012). It is surprising therefore, that uncertainty assessment is so infrequently applied in the field of embodied carbon. In prior work on uncertainty in embodied carbon assessments of buildings, statistical methods have typically been applied. These methods are not well suited to assessing scenario uncertainties, which are by definition not readily characterised in terms of statistical distributions or quantitative uncertainty ranges. So such studies either do not take account of these sources or else the results do not clearly differentiate the effect of sources of scenario uncertainty from statistical uncertainties.

One approach to eliminating some sources of scenario uncertainty is to follow common standards (Heijungs & Huijbregts, 2004), such as those for producing EPD. This approach works on the basis that data produced in compliance with a standard are expected to be based on broadly comparable assumptions and methods. As such, this approach is likely to be most useful when undertaking comparative assessments. However the results of this research show that EN 15804 (British Standards Institution, 2014a), the standard for producing EPD, is currently interpreted in different ways for different materials. A particularly pertinent example for the construction industry is that of steel, where different allocation methods are applied for the co-products of steel production. All the steel industry EPDs reviewed for this research apply system expansion, a form of physical allocation (e.g. Institut Bauen und Umwelt e.V., 2013). Yet the cement industry, which utilises much of the slag from the blast furnace stage of steel production does not apply any allocation to this co-product (Institut Bauen und Umwelt e.V., 2014b).

EPD results are rarely presented with information about either statistical or scenario uncertainties. In some EPDs, the use of multiple scenarios to model uncertainties has been applied in the case of the end of life environmental impacts. For example, EPD for timber products produced by the Australian timber industry body, Wood Solutions Australia (2015b, 2015a), provide data for two alternative landfill scenarios and for incineration with energy recovery. This research builds on this approach by extending it to identify and model uncertainties at other stages in the life cycle. Moreover, it supplements this with an assessment of the statistical uncertainty range that remains once scenario uncertainty has been accounted for. The use of decision trees to depict the main sources of scenario uncertainty affecting a particular EPD and to highlight which alternative assumptions or methods have been used to generate the reported data would improve their transparency and comparability.

In light of the large uncertainty ranges demonstrated in this research, it is somewhat surprising that EN 15978 (British Standards Institution, 2011a) and EN 15804 (British Standards Institution, 2014a) currently make no mention of uncertainty or uncertainty assessment. Updating the standards to include recommendations or requirements for uncertainty assessment is therefore strongly recommended and would bring them into line with ISO 14040. The diagrams to depict key sources of scenario uncertainty that were developed and presented in Chapter 6, and the methods used to define them could be incorporated into the existing guidance and requirements. Including such diagrams in EPD, for example, to illustrate which assumptions and methodological choices have been made, would increase their transparency and comparability.

8.2.5 The Effect of Scenario and Statistical Uncertainty on Comparative Embodied Carbon Assessments

In the material comparison case studies in Chapter 7, the effects of scenario and statistical uncertainty on comparisons of design alternatives to reduce embodied carbon were analysed. The results have shown that when these sources of uncertainty are taken into account, estimates of embodied carbon savings achievable through changing material specifications vary dramatically between different scenarios. For all three case studies assessed, the effect is so great that whilst some scenarios show significant embodied carbon savings are achieved, alternative scenarios for the same material substitution lead to increased embodied carbon. These results highlight the importance of considering the effects of these sources of uncertainty when making such comparisons.

In some cases, there may be a financial cost to the use of an alternative material. In these situations, the designers and other project stakeholders may be assessing the cost of a number of different alternative carbon reduction or carbon abatement initiatives. Often the decision is based on the lowest cost per unit of carbon abated. The marginal abatement cost (MAC) is an environmental economic tool for identifying the most cost effective measures to mitigate climate change impacts (Kesicki & Strachan, 2011). In the case of a supermarket, different carbon abatement measures, such as reducing embodied carbon through material substitution could be assessed using the MAC. However, if the estimates of carbon savings are subject to uncertainty then the MAC is also uncertain. This introduces financial as well as environmental risk to the decision, since the selected investment might actually have a higher MAC if the assumptions and methods on which it is based are changed. In such cases, an assessment of uncertainty is particularly important to allow decision makers to fully understand these risks.

8.2.6 Strategies to Mitigate Scenario Uncertainties

By considering scenario uncertainties, designers and policy makers may be able to take actions which could make particular assumptions or methodological choices more justifiable or defensible. In this way, the scenario uncertainties and the financial or environmental risks they introduce can be mitigated. For each material, the most effective actions to reduce uncertainty and risk would be dependent on which sources of scenario uncertainty have the greatest impact on the outcomes.

8.2.6.1 Steel

The assessment of scenario uncertainties affecting the embodied carbon factor for steel showed that the main consideration is how the data are aggregated. If data are aggregated for the whole steel industry, then this masks the relatively higher embodied carbon impacts of sheet steel, compared to steel sections. This is due to the need for lower levels of impurities to manufacture sheet steel, which means it must be manufactured via the more carbon intensive BOF process, which accepts less scrap than the EAF process. The argument for aggregating data in this way has been discussed in section 6.2.2.4, and relates to the constrained market for scrap steel. In discussions on this matter in academic research (e.g. Jones, 2009) and industry reports (e.g. World Steel Association, 2011), it has been argued that introducing a requirement for the steel in a building to have a high recycled content has no net benefit and could in extreme cases lead to greater inefficiencies in steel production. The rationale for this argument is that given the constrained market for scrap steel, attempting to increase the recycled content in the steel for one building would only reduce availability of recycled steel elsewhere. On this basis, there is no benefit to be realised from penalising BOF steel with a high carbon factor and crediting EAF steel with a lower carbon factor. The two production routes are both part of a single system, which is already achieving near maximal efficiency in terms of the rate of steel recovery and recycling (World Steel Association, 2011). As long as the total demand for steel continues to grow and there is demand for sheet steel and other products that can only be made via the BOF route, the supply of scrap will not be able to meet demand.

Yet there is a flaw in the argument, since it is based on the assumption that the only alternative to EAF steel, with its high recycled content and relatively low carbon factor, is BOF steel. Whilst this may be true in some cases, there are many applications in construction where viable alternatives to steel exist. Case studies 7-1 and 7-2 in this research, which assessed the replacement of steel with alternative timber solutions for a supermarket's structural frame and roof respectively, are just two examples of such applications. If more emphasis were placed on ensuring the steel used in buildings has a high recycled content, the constrained availability of this steel could conceivably lead to increased use of alternative materials.

On the basis of the uncertainty assessment results presented here, a business like Sainsbury's could decide to prioritise the use of alternative materials to sheet steel wherever possible. If others in the construction industry did likewise, demand for sheet steel, and hence total demand, could decrease, albeit by a relatively small amount. Yet it could be argued that adopting such an approach provides a reasonable justification for the use of disaggregated embodied carbon data for steel. In such a scenario, incentivising the use of high recycled content EAF steel through the use of carbon factors that reflect the true carbon emissions of this process could lead to a net benefit.

8.2.6.2 Timber

For timber, the choice of whether to include sequestered carbon has been shown to have the greatest effect on the embodied carbon factor. A straightforward way to make its inclusion more defensible is to specify that timber is from certified sustainable sources (Darby, 2014). Such forests are managed to ensure that there is no net deforestation. Thus as timber is harvested, it is replaced with new growth, which increases the amount of carbon sequestered overall. It is therefore reasonable to give a credit to the harvested timber equivalent to the amount of carbon stored during the growth cycle.

One of the scenarios where timber is sent to landfill at the end of its life resulted in lower cradle to grave emissions than the alternative energy recovery or material reuse scenarios. The embodied carbon of glulam assessed in this scenario was found to be -0.36 tCO_2e per cubic meter if sequestration in the growth cycle was credited (+0.428 tCO_2e/m^3 if not). By contrast, energy recovery and reuse were found to give embodied carbon factors of +0.395 and +0.368 tCO_2e/m^3, respectively (1.183 and 0.368 tCO_2e/m3 without sequestration). The alternative landfill scenario, which assumes a higher rate of decay, was shown to result in of 0.483 tCO_2e/m^3 (1.271 tCO_2e/m^3 without sequestration). Thus these two alternatives produced both the highest and lowest values for embodied carbon. This serves to illustrate how great the effect of scenario uncertainties can be on the embodied carbon results. The difference between the two scenarios is made greater by the fact that, due to partially anaerobic decay, a proportion of the biogenic carbon released from the timber is emitted as methane. The GWP of methane is 25 times greater than that of CO_2 (IPCC, 2007). The low rates of decay have been demonstrated in controlled tests where bulk timber is sent to landfill, whereas the tests that produced high rates of decay were based on ground timber (Wood Solutions Australia, 2015a). On the evidence of this assessment alone, the most carbon efficient approach to dealing with timber at the end of life appears to be to send it to landfill with as little processing as possible in order to minimise rates of decay. This can be seen as a form of carbon capture and storage. Carbon dioxide is sequestered from the atmosphere whilst the tree is growing and is stored as biogenic carbon in the timber. When the timber is harvested, this carbon remains stored in the timber product. If the low decay-rate assumption is valid, the when that timber product is disposed of, the carbon is not released back to the atmosphere as happens when timber is burned to produce energy.

However, as has been highlighted Chapter 6 (section 6.2.3.2), the apparent end of life emissions from reuse or recycling of timber are misleading. These emissions are included for carbon accounting purposes, to allow the user of the recycled timber to claim credit for sequestered carbon without this leading to double counting of emissions between the two first and second uses. They do not relate to actual emissions of carbon dioxide to the atmosphere and users of the data must take this into consideration when basing design, investment or policy decisions on such results.

The waste hierarchy approach set out in the EU Waste Framework Directive (European Union, 2008) sets the order of priority or preference for waste treatment. Prevention of waste is the most preferable approach followed by reuse, then recycling, and then energy recovery. Disposal to landfill is the least favoured waste treatment option and this is reflected in UK Government initiatives which have explored policy measures to prevent timber being sent to landfill (Department for Environment, Food and Rural Affairs, 2013). The results of an embodied carbon assessment should therefore not be considered in isolation but in conjunction with other indicators and guidance for achieving environmental sustainability across the building life cycle.

8.2.6.3 Insulants

For mineral wool, the material type has an important effect on the embodied carbon. The analysis in chapters 6 and 7 suggests that for reducing embodied carbon, glass wool should be specified over stone wool or generic mineral wool. This is more important than considerations about the end of life treatment in terms of maximising estimated embodied carbon savings.

8.2.6.4 Cement and Concrete

For concrete, the two most commonly used SCMs, PFA and GGBS, have highly uncertain embodied carbon factors due to the different methods of allocation that are applied. This suggests that estimates of carbon savings based on the use of these two materials should be treated with some caution. As Crossin (2015) has argued, there are environmental benefits to the use of these materials as long as supply is greater than demand. Once the demand exceeds available supply, the use of PFA or GGBS in one building merely prevents its use elsewhere. For this reason Crossin proposes that the allocation method should be determined by whether or not the market for SCMs is constrained in this way. Darby (2014) investigated the balance of supply and demand for these two materials and identified that data to establish this ratio accurately for the UK are not readily available. He concluded, however, that close to all the available GGBS in the UK is already being utilised. Further, due to predicted reduction of coal fired power, to comply with climate change laws, he expects the production of PFA to reduce over time. Despite these conclusions, Darby proposes that economic allocation should be used for these two materials, a conclusion which stands in contradiction to Crossin's proposal (2015). Thus there continues to be contention and debate around the most appropriate allocation method. In this research, it has been argued that these alternatives are a source of scenario uncertainty and should be treated as such using the uncertainty assessment method demonstrated. In this way, the lack of consensus is not concealed from decision makers but its effect is assessed and communicated. This allows the decision maker to incorporate the risks into their decision. Where SCMs can be incorporated into the concrete mix without incurring additional costs or impacting on programme, the risks are minimal. However, the results from Chapter 7 call into question the widely held industry view that pushing for higher and higher levels of PFA or GGBS in concrete is always an appropriate carbon abatement initiative. The concrete industry should seek to develop viable alternative SCMs to PFA and GGBS and the efforts to reduce the embodied carbon of OPC should be prioritised. For example, the possibility of replacing the more energy intensive production routes such as the semi-wet and semi-dry methods should be investigated further.

8.2.7 Additionality of Estimated Emissions Reductions

In each of the material comparison case studies, sources of scenario uncertainty affect both the standard and the low carbon alternative materials. This uncertainty gives scope for the selective use of data that increase the apparent savings. For example, when comparing low carbon concrete against concrete with 100% OPC (or CEM I), the embodied carbon savings appear higher than when the comparison is against a concrete based on a weighted average of UK cements. This raises the issue of the additionality of emissions reductions. For estimated emissions reductions to be considered additional, they should be calculated against a baseline that is an accurate reflection of what would have happened if the reduction initiative had not been carried out (CDM Rulebook, n.d.). The concrete industry data suggests that average UK cement has a lower carbon factor than 100% OPC because of the common use of SCMs. It could therefore be argued that this average data provides a more realistic baseline for comparison than 100% OPC since the carbon factor of 100% OPC is not representative of typical or standard practice.

This is an issue which has largely been overlooked in embodied carbon research to date. Where embodied carbon has been assessed for a building and reduction initiatives have been implemented, it is common for claims to be made about the emission reduction that was achieved (e.g. Carey, 2015; Cullen et al., 2011; Deloitte, 2010). These savings may be reported as percentages or in absolute terms. In either case, how the baseline was calculated, against which savings are estimated, is a highly relevant consideration. As embodied carbon assessment and reduction becomes more commonplace, such claims must come under greater scrutiny. A common approach to establishing baselines is needed if companies, design teams and policy makers are to meaningfully compare progress towards reducing the embodied carbon of buildings. Already, credits are available through the Leadership in Energy and Environmental Design (LEED) sustainability certification scheme for achieving a 10% reduction in embodied environmental impacts, including embodied carbon. The 10% reduction is measured against a baseline building which 'must be of comparable size, function, orientation, and operating energy performance' and the assessment must use the same LCA tool or software and datasets and be ISO 14044 compliant (US Green Building Council, n.d.). Yet the evidence from the uncertainty assessment carried out here is that current standards are still being interpreted in different ways. In particular, ambiguity as to the appropriate selection of allocation methods for co-products is an ongoing and unresolved source of contention (Habert, 2013). This suggests that the LEED definition of the baseline building may not be adequate to ensure emissions reductions estimates only include genuinely additional savings.

The methods developed and applied in this research do not provide a solution to the problem of how to define baselines. This was not one of the original research objectives and so has not formed part of the scope of the work. However, it is argued that the inclusion of uncertainty assessment, and the communication of assumptions using the decision tree diagrams improves the transparency of embodied carbon assessment results. This in turn allows for improved comparisons between studies, since apparent inconsistencies can be linked to differing assumptions and methods. The wider use of uncertainty assessment in embodied carbon studies and research is an important first step to facilitate discussion and debate about how baselines can be appropriately and consistently defined.

8.3 Limitations of the Chosen Research Methods

8.3.1 The Potential and Limitations of BIM to Facilitate Design Stage Embodied Carbon Assessments

The research has demonstrated that BIM can provide a means to generate material quantity data for a whole building in order to undertake an embodied carbon assessment. The approach implemented here was adapted from ideas proposed and trialled by Jrade and Abdulla (2012) and Schwartz et al. (2016). Their work sought to establish a link between the quantity data from a BIM model and a particular set of carbon factor data. Jrade and Abdulla base their method on a specific building LCA tool and incorporate identifiers from the tool into the meta-data for objects in the BIM model. Schwartz et al. propose the use of semantic web technology as a means to transfer EPD data into a machine-readable format. In this way, the EPD data can be analysed within the BIM environment. In this research the link was established by creating a list of material categories which were common to both the carbon factor data and the BIM quantity data. This allowed for the step of assigning carbon factors to BIM objects to be semi-automated within an Excel spreadsheet using a macro.

This approach overcomes a key limitation of Jrade and Abdulla's method, where the embodied carbon or LCA assessment can only be conducted in the chosen tool. The commercially available tools reviewed for this research (see section 3.3.3) were all found to restrict the available embodied carbon factor data to a specific predefined database with no option to update or edit the built-in values.

In comparison to the semantic web method, the use of common material category names adopted here offers more straightforward implementation without the need for complex programming. Moreover, it is not restricted to using data from EPDs only, although it may be possible to extend the semantic web method to incorporate other data sources. The advantage of the greater sophistication of semantic web programming is that, if implemented, it would overcome one of the major limitations of EPDs, which is their current format. All the major EPD platforms and providers currently store and distribute EPDs using the portable document format (PDF). As such the EPDs are static and the data cannot be manipulated or analysed without first being manually copied into a computer programme such as a spreadsheet or database. In the assessments conducted here, a spreadsheet table of carbon factors was created, starting with the *Inventory of Carbon and Energy* (Hammond & Jones, 2011), a large publically available carbon factor dataset, reformatted to follow the modularity principles of EN 15804 (British Standards Institution, 2014a). This was supplemented with relevant carbon factors from EPD and other sources. Whenever a new material is required or updated data are made available, this must be copied into the table. This interim step would not be necessary if the data were stored online in a machine readable format. Reducing the need for data re-entry was identified by Díaz and Antön (2014) as one of the main requirements for integration of LCA and BIM and therefore it is argued that the lack of availability of EPD data in a digitally readable form is a key barrier to better integration of BIM and LCA methods, which needs to be overcome.

8.3.1.1 Improving the Suitability of BIM Models to Generate Quantities for Embodied Carbon Assessments

By developing and applying an approach to integrating BIM and embodied carbon assessments, it has been possible to identify some of the main limitations of Sainsbury's current BIM models for this purpose. Broadly the aspects of the models that restrict their usefulness for this application are either related to simplifications or to errors. Within these two categories, six different types of limitation or barrier to extracting appropriate quantity data were identified. These were:

- Simplified geometry
- Composites not fully modelled
- Materials not specified to the required level of detail
- Quantities or dimensions not available
- Objects not clearly or not consistently named
- Duplicated objects (both within a single file and due to incorrect alignment of multi-file models)

It is assumed that errors in the models are detrimental to their usefulness generally. The fact that they also have negative impacts on the implementation of BIM-integrated embodied carbon assessments simply serves to underline the importance of accurate modelling. The model simplifications however, presumably serve to make the modelling process more efficient. A number of potential applications of BIM to support sustainable design of buildings have been demonstrated and discussed in previous studies. Examples include the use of BIM models to support energy modelling, sustainability certification and LCA of buildings (Dowsett & Harty, 2013; Jrade & Abdulla, 2012; Stadel et al., 2011). On the evidence of this research, the benefit of model simplifications, for example in terms reduced modelling time, should be reconsidered in light of the potentially negative effect this can have on these further applications of BIM. In particular, for supermarkets, consideration should be given to creating accurate model geometry and meta-data for the steel and concrete elements of the building as early as possible in the design process as these have been found to have the greatest impact on embodied carbon. This includes the sub-structure and super-structure as well as the retail shelving and chilled cabinets.

8.3.1.2 Availability of BIM Data During Early Design

One criticism of using BIM to support embodied carbon or other environmental sustainability assessments is that the level of detail required in the BIM model may only be reached when the design is relatively well developed (eTool, 2014). Many of the key decisions affecting the embodied carbon, such as the building form, type of foundations and key materials in the substructure and superstructure, may have already been made by the time the BIM model is developed. To some degree, the evidence of the building case studies in Chapter 4 supports this view. For example, the “store on stilts” configuration of Sainsbury’s Thanet was found to be a key factor in the greater embodied carbon of the substructure and superstructure compared to the 60k Model store. Embodied carbon emissions per square meter of floor area were 18% higher than the 60k Model when comparing only the sub- and super-structures. Similarly, the use of timber for the structural frame and roof at Leicester North contributed to that building having an embodied carbon intensity of 416 $kgCO_2e/m^2$ compared to 575 $kgCO_2e/m^2$ for the 60k Model, a reduction of 25% (when fit out items and refurbishments were excluded from both to ensure like for like comparison). These are both aspects of the buildings’ designs which are likely to have been established during the feasibility assessment stage, before the detailed BIM models were completed.

However, for supermarkets, where there is a relatively high level of repetition of key design features, the BIM model is expected to be available earlier in the design process. Sainsbury’s uses the 30k and 60k Models, discussed in section 4.6 of Chapter 4, as templates from which to develop new store designs. The BIM models established for these two template stores can be adapted, allowing a BIM model for a new store to be created relatively more quickly than when starting a model from scratch. It is therefore argued here that for supermarkets, the use of BIM for carrying out embodied carbon assessments can provide useful results even in relatively early design stages.

Additionally, as more buildings are assessed, Sainsbury’s can collect data on the embodied carbon intensities of typical building configurations and sizes, in much the same way as has been done in section 4.6 of Chapter 4. This data can be used to support very early estimations of the impacts on embodied carbon of feasibility stage decisions. The research has already shown the effects of selecting a “store on stilts” configuration or the use of timber in different parts of the construction. Similar results can be produced by using the BIM-integrated embodied carbon assessment approach developed here to assess more buildings.

8.3.2 Limitations of The Uncertainty Assessment Method

The approach to uncertainty assessment that has been developed and tested in this research has been shown to yield useful results, leading to important insights about the way uncertainty is understood and how it may affect design decisions. Nevertheless, different elements of the method are subject to limitations which are discussed here. Possible options to mitigate or overcome these limitations in future work to further develop these methods are also suggested.

8.3.2.1 Limitations of the Data Quality Matrix

The data quality matrix method was used in this research to rank different sources of carbon factors in order to prioritise their selection. The broadly defined categories of carbon factor source represent a potential weakness. It is likely that different data from the same source category, for example two different government data sets, would receive different scores if they were individually evaluated and given scores. Other studies have used the data quality matrix in this way, assigning different scores to each data input. This is a more time and resource intensive approach, which may be why in other work the data quality scores were assessed by the research team (e.g. Pomponi et al., 2017), and not through expert elicitation as was the case here.

The differences between the scores elicited for the same source of carbon factor from the ten experts indicate that there is an element of subjectivity involved when evaluating qualitative features of data. It also suggests that each expert may have interpreted the data quality criteria defined in the research differently or have different levels of understanding or familiarity with each of the carbon factor sources evaluated. The subjectivity in data quality scoring suggests that obtaining a range of expert views is important to ensure the results are not skewed or biased towards the opinions of one individual or one team of researchers. Increasing the sample size, for example using a survey to obtain data quality scores, would potentially further reduce the likelihood of bias in the results. However, the effectiveness or viability of such an undertaking would be limited by the availability of expertise. The purpose of eliciting expert judgments is to characterise existing knowledge and such judgements may be based on ‘a wide range of data and information from direct empirical evidence to theoretical insights’ (U.S. Environmental Protection Agency, 2009, p. 22). The robustness of these judgements is thus more directly related to the level and appropriateness of expertise of the participants than to the sample size of experts consulted. It is argued here that the selection of appropriate expertise for an elicitation should therefore be prioritized over increasing the sample size.

8.3.2.2 Limitations of Expert Elicitation

The expert elicitation approach to uncertainty assessment has been widely applied in various fields related to environmental management. Cooke and Goossens (1999) assert that ‘increasingly, expert judgment is recognized as just another type of scientific data, and methods are developed for treating it as such’ (p. 9). Nevertheless the method has limitations, which are largely related to the subjectivity associated with defining expertise and selecting experts, as well as the judgements and opinions elicited.

Proponents of the method argue that ‘subjectivity is inherent to scientific methodologies’ and ‘in traditional scientific research, the choice of methods may influence data, which may influence conclusions.' (U.S. Environmental Protection Agency, 2009, p. 24) The subjectivity in expert elicitation is perhaps more explicitly apparent than in other methods.

Methods to overcome subjectivity and potential for bias in data elicited by expert judgement have typically drawn heavily on the theory of heuristic biases developed by Tversky and Kahneman (1975) (see section 2.7.3 of the literature review). However, work in the field of psychology has refuted a number of Tversky and Kahneman's claims, indicating instead that how the problem is framed is the most important factor affecting the reliability of elicited judgements (Kynn, 2008).

The experience of this research supports the notion that the framing of the problem or question that is put to experts in the elicitation is a key factor in enabling them to provide meaningful responses. In the group elicitation, the experts were asked to estimate uncertainty ranges for a selection of materials by providing maximum and minimum values of embodied carbon. This process highlighted the presence of sources of scenario uncertainty which meant that the experts were not able to meaningfully define ranges in terms of maxima and minima. Of the 10 experts who attended the group elicitations, only 2 provided any data in response to this question.

To overcome this, the elicitation protocol was adapted for the individual expert interviews. The elicitation questions were reframed to allow the experts to assess different levels of uncertainty in different ways (see section 5.3.3.2). Sources of scenario uncertainty were assessed qualitatively using the decision-tree diagrams. The quantitative data to model each of these elicited scenarios was then sourced from published carbon factors, thus reducing the potential for subjectivity and bias to affect the results of the scenario analysis.

Quantitative estimates were elicited only for remaining sources of statistical uncertainty. Furthermore, the technique used initially to elicit these quantitative ranges was altered. Instead of asking experts to specify the extremes of the uncertainty range, the interval method was used (Slottje et al., 2008; and see section 5.3.3.2.2 for details). In the individual elicitations, six of the eight experts provided quantitative estimates in response to this question (see Table 6-4). This was an improvement on the original response rate achieved in the group elicitations but suggests that there is still scope to improve the problem framing. One of the participants (P) who did not provide an estimate in response to this question in the individual elicitation commented that 'It's too big a question […], lots of things to consider; too many.' This suggests that further disaggregation of the possible sources of statistical uncertainty affecting carbon emissions for a material may lead to improved response rates. This would require access to the underlying inventory data that are used to calculate a material carbon factor. In this way, experts could be asked to estimate uncertainty ranges for data such as the energy efficiency of production or the raw material input quantities and these could then be used to model statistical uncertainty in the resultant carbon factor. Risbey et al. (2006, p. 5) describe a process for disaggregating the input variables to a model, which could be applied here to reframe the elicitations. Under such an approach, the definition of selection criteria for experts may need to be reviewed since knowledge of factors such as process efficiencies may require a different field of experience and expertise than knowledge of embodied carbon factors.

8.3.2.3 Expert Selection

In this research, the expertise of participants was assessed based on a combination of quantitative and qualitative factors. The quantitative factors were the number of years' experience of working in a relevant field, the number of relevant qualifications and publications an individual had, and the number of embodied carbon assessments they had undertaken. The qualitative assessment of expertise was related to the reputation of the individual in the field of embodied carbon. This was determined based on the views of the research team and, to a lesser degree, the opinions of the other experts. All the experts initially contacted were given the opportunity to propose the names of colleagues or acquaintances that they felt had the necessary credentials. These additional candidates were then included for consideration and three of the eighteen participants were selected in this way.

It is important to acknowledge that the relatively small number of people in the UK with adequate expertise, and the availability and interest of those people to participate in the elicitations, were both important influencing factors in the selection process. Of the seventeen participants, only three were available to participate in both rounds of elicitations. A further four of the experts initially contacted were not available to participate at all.

8.3.2.4 Combining Elicited Judgements

Whether and how to combine different expert judgements is a subject of ongoing debate in the literature (Knol et al., 2010; Cooke & Goossens, 1999; Keith, 1996). When dealing with quantitative outcomes which form inputs to a model, it is generally necessary to combine multiple elicited uncertainty ranges into a single range. This was the case for the estimated statistical uncertainty ranges reported in chapter 6 and applied in the material comparison case studies in chapter 7. It was also necessary to aggregate the data quality scores elicited in order to determine a final ranking of the sources of carbon factor data. One approach is to use an unweighted average of all responses. This approach was used to combine the data quality scores. Alternatively, weightings can be applied to each expert's response based on some measure of expertise or performance. The most common method of weighting responses is to include a known variable, often called a seed variable, in the elicitation exercise (Knol et al., 2010). The experts' responses to each of the unknown variables are then weighted according to how accurately they estimated the seed variable. A third alternative is to take a precautionary approach and use the worst case estimate for each variable. This approach was used here for the elicited estimates of statistical uncertainty. The use of performance indicators was considered but was not included for either the data quality scores or the estimates of statistical uncertainty. The definition of appropriate seed variables has the potential to introduce further subjectivity and the other two approaches were considered adequate for the purposes of this research. For the data quality scores, the qualitative nature of the scoring criteria in the assessment meant that it would have been difficult to define a relevant seed variable. Similarly, for the elicited estimates of statistical uncertainty, the experts were asked to consider different materials based on their expertise and so it would have been necessary to identify a different seed variable for each expert to suit their area of knowledge. For these reasons it was considered that this would not provide a more robust basis for subsequently weighting their responses. Therefore, the precautionary approach was considered preferable to weighting in this instance.

For the scenario uncertainties elicited, combining responses is less contentious since the responses supplement each other. The decision tree diagrams therefore present the perspectives of all the experts whose judgments were elicited for that material. It was therefore not necessary to introduce any form of weighting to this aspect of the elicitation results.

8.3.2.5 Validation of Results

Since uncertainty assessments have only been carried out in a small number of previous studies, there is limited data available with which to independently validate the results obtained in this research. Moreover, no examples of previous uncertainty assessments of embodied carbon that separate scenario and statistical uncertainty were identified. Therefore, direct comparison of the effects estimated here for these two distinct groups of uncertainties was not possible. For statistical uncertainties, the expert estimates have been shown to be of a similar order of magnitude to the uncertainty ranges given in the Bath ICE database, which is one of the most comprehensive reviews of embodied energy and carbon data published to date. However, the ranges given in the ICE database are for embodied energy rather than embodied carbon and do not separate scenario and statistical uncertainty. For timber, the statistical uncertainty ranges estimated in this research were compared with those presented in Rüter and Diederichs (2012). Since their ranges are based on their own inventory data and results, it can be assumed that these only represent statistical uncertainties. This comparison suggests that the estimates elicited from experts in the interviews conducted for this research may underestimate the actual variation due to statistical uncertainty. These should therefore be seen as preliminary estimates. The possibility that they may be underestimates serves to underline the importance of uncertainty assessment. The evidence of the material comparison case studies presented in chapter 7 shows that the estimates of statistical uncertainty elicited here, when combined with scenario uncertainty, can lead to situations where material choices intended to reduce embodied carbon may actually lead to increased embodied carbon.

Embodied carbon assessment, and building LCA generally, would benefit from the publication of statistical uncertainty ranges in EPD such as those given in Rüter and Diederichs. This is something that should also be considered for inclusion in future updates to EPD and PCR requirements under EN 15804.

8.3.2.6 Limitations of the Methods used to Quantify Uncertainty

The uncertainty assessment method developed here has been demonstrated for three case studies involving comparative assessments of two alternative materials for just one part of the building. Whilst this provides useful insights into how uncertainty can affect the estimation of embodied carbon savings, it does not provide an estimate of the overall uncertainty in the total cradle to grave embodied carbon of an entire supermarket building. To achieve this would require further elicitations to be conducted for each material in the building. This would be a resource intensive undertaking, requiring the identification and selection of suitable participants with the necessary expertise.

The scenario assessment method adopted to evaluate the effect of uncertainty in the material carbon factors on the results of the comparison can result in large numbers of results. For combinations of different materials in composite building elements, the total number of scenarios that must be modelled is the product of the number of scenarios for each constituent material. In the example of Case Study 7-3, the combination of different materials in the concrete resulted in up to 960 different scenarios. This approach would therefore be impractical when assessing uncertainty for a whole building. With the large numbers of different data inputs for a whole building assessment probabilistic modelling, such as Monte-Carlo simulation, becomes necessary. However, as has been discussed in section 5.3.1.2 of Chapter 5, the disadvantage of such methods is that they are not well suited to assessing scenario uncertainties since these are not generally subject to probabilities but represent subjective choices (Skinner, 2012; Walker et al., 2003). Moreover, such simulations typically require a large dataset in order to generate probability distributions for the uncertainty of each input (e.g. each carbon factor). Such data is, in most cases not available. Recent research by Pomponi et al. (2017) has, however, demonstrated that it may be possible to achieve meaningful results with Monte-Carlo simulation when only maximum and minimum values are known for a given input parameter. This would, for example, allow a Monte-Carlo simulation to be conducted based on the estimates of statistical uncertainty elicited from experts in this research.

This suggests that a combination of the two approaches could provide a useful means of conducting uncertainty assessment at both the building level and for specific comparisons of different materials for a given part of the building. The uncertainty assessment for the building could be conducted using Monte-Carlo simulation to evaluate the effect of statistical uncertainties on the final results. Then detailed scenario analysis as proposed in this research could be conducted to evaluate the effect of statistical and scenario uncertainty on the estimated savings achievable through specific embodied carbon reduction initiatives.

9 Conclusions and Recommendations for Future Work

9.1 BIM-integrated Embodied Carbon Assessments

The research has demonstrated that BIM has the potential to streamline the process of conducting embodied carbon assessments during the design. However, on the basis of three building case studies assessed here, current modelling practices limit the potential for automation. This makes it necessary to introduce proxy data in the form of geometric conversion factors to correct erroneous quantities. Businesses like Sainsbury's that wish to maximise the potential of their BIM models to facilitate embodied carbon assessments or, indeed, full LCA should consider the following points:

- Avoid simplifications of model geometry (for example modelling objects with hollow cross-sections as solids), particularly where these are expected to have a high embodied carbon impact
- Provide adequate detail in the models of composite objects so that quantities of each material in the composite can be extracted
- Specify materials as fully as possible in the model
- Ensure that object names provide a clear indication of what the object is and facilitate multiple selections and searches to streamline the quantity take-off exercise.
- Seek to reduce the number of errors in models, and particularly those that lead to duplicated objects such as misalignment of multi-file models (BIM models may comprise several linked files and if these are misaligned, the software is unable to recognise objects that appear in more than one file and treats these as two distinct objects. Correct alignment ensures such duplicates are only counted once in quantity take-off data)

9.2 Environmental Product Declarations and Other Sources of Carbon Data

The importance of EPDs as a source of carbon factor data for materials has been highlighted in the literature. The expert elicitations reported in Chapter 6 support this and it was concluded that in general, where suitable EPD data are available; these should be used in preference to other sources. The results of this research suggest that, in terms of data quality, carbon factors should be selected based on the following order of preference:

1. EPD (EN 15804 compliant)
2. Factor from commercial LCA database
3. PAS 2050 compliant carbon footprint

4. Industry data
5. Government data
6. Factor derived/aggregated from literature

Currently, BIM-based embodied carbon assessment tools, including the approach developed as part of this research, require a dedicated embodied carbon dataset. This means that the desired goal of preventing data re-entry has yet to be achieved. To do this, EPD or other sources of carbon factors should be stored and distributed in a machine-readable format rather than as static documents.

The continually increasing availability of EPDs will make obtaining carbon factor data for materials more straightforward. However, one area where the greater number of EPDs has not resulted in an equivalent increase in the availability of carbon data is for construction activities. It is argued here that whilst the onus to develop EPDs continues to be placed on product suppliers and manufacturers, there will be a persistent lack of data for this life cycle stage. Product manufacturers are not generally responsible for the carbon emissions occurring during construction and do not have access to the necessary data to include this life cycle stage in their EPD. Moreover, it would be difficult to find any meaningful basis by which to allocate construction site emissions to specific materials in a building. In addition to promoting EPDs, the construction industry should be encouraged to find other ways to address the lack of data for this stage of the building life cycle.

9.3 Embodied Carbon of Supermarkets

The three case studies modelled using the BIM-integrated approach developed for this research support the evidence of prior studies that cradle to grave embodied carbon of supermarkets is dominated by steel and concrete. For the steel framed case study buildings, structural steel represents the majority of the cradle to gate embodied carbon. However, when considering the whole life-cycle and when fit out items are included in the scope of the assessment, the steel shelving was found to have the greatest overall impact. This is due to the high volumes, the high carbon factor of sheet steel relative to steel section, and the frequent replacement and refurbishment cycles that were assumed in the calculations based on currently reported practice.

Different configurations and types of construction assessed in the building case studies were found to have notably different embodied carbon intensities (carbon emissions per square metre of floor space). Siting the carpark beneath the sales area in what is known as a “store on stilts” arrangement was shown to increase the embodied carbon intensity by 18% compared to a supermarket located at ground level with the car park adjacent. The use of timber for the frame (glulam) and roof (insulated timber cassettes) of the building was found to reduce the embodied carbon intensity by 25% compared to using a steel frame and insulated steel deck roof.

For many types of buildings, the greatest scope to reduce embodied carbon is at the very early stages of design. However, at these early stages the data are typically not available to conduct detailed embodied carbon assessments since material specifications and accurate quantities are not available. Thus, by the time an assessment of the embodied carbon is carried out, important decisions such as the choice of structural material or the built form may already be decided and making changes may lead to costly delays or redesigning.

However, for supermarkets, this problem can be mitigated in two ways. By conducting further assessments of buildings with a range of different configurations using the BIM-integrated approach developed here, Sainsbury's would be able to establish benchmarks for the embodied carbon intensity of each typical configuration. These could be used to support the consideration of embodied carbon at the earliest stages of feasibility and design, when BIM data are not yet available. Moreover, due to the relatively high level of standardisation in supermarket designs, compared to other types of commercial buildings such as offices, the necessary data to create accurate BIM models could be available earlier in the design process. Through increased standardisation of material specifications in particular, Sainsbury's and other companies building high volumes of the same or similar buildings could conduct embodied carbon assessments much earlier in the process.

9.4 The Effects of Uncertainty in Embodied Carbon Assessments of Supermarkets

Sources of uncertainty that affect the embodied carbon factors of building materials can be divided into two distinct groups based on the level of uncertainty that they introduce. There are uncertainties related to different assumptions and methodological choices which can be made when estimating carbon factors for a material. These introduce levels of uncertainty which are characterised by alternative scenarios where the probability of each scenario is not known or cannot be meaningfully determined. The second group of sources of uncertainty are characterised by levels of uncertainty where it is possible to establish quantitative ranges for a given carbon factor.

In this research, relevant sources of scenario uncertainty for eight different materials were identified through a combination of literature review and expert elicitation. Examples of these sources include different levels of data aggregation, different methods for co-product allocation, different end of life scenarios, and different assumptions about physical properties of the materials. An approach for representing and communicating these sources of uncertainty in a graphical form for a given material was developed using decision trees to represent the assumptions or methodological choices made when estimating embodied carbon factors.

Estimates of the range due to statistical sources of uncertainty were also elicited from experts in embodied carbon for the eight materials. The elicited values are listed in Table 9-1.

Table 9-1: Estimates of the uncertainty range due to sources of statistical uncertainty elicited from either two or three experts

Material	**Statistical Uncertainty Estimate** Lower Bound	 Upper Bound
Steel	-15 %	30 %
Timber	-20 %	20 %
Concrete (including cement, aggregates and SCMs)	-20 %	25 %
Insulants (Mineral Wool and PU)	-20 %	20 %

Where experts' estimates differed, the values reported here are the highest and lowest figures for the upper and lower bounds respectively
SCM = supplementary cementitious material and includes ground granulated blast furnace slag and pulverised fly ash
PU = polyurethane

9.4.1 Key Sources of Uncertainty

The effects of both statistical and scenario uncertainty on the carbon factors for each of the eight materials were assessed. It was found that in all cases examined, the scenario uncertainties were estimated to have the greatest impact.

The sources of scenario uncertainty with the greatest impact on carbon factors, differed between the materials assessed as shown in Table 9-2.

Table 9-2: Key sources of scenario uncertainty identified for each of the eight materials assessed

Material	**Key sources of scenario uncertainty**
Steel	• Choice of the level of data aggregation: are data aggregated at industry level or at individual production route level? • Method used to account for recycled content
Timber	• Inclusion or exclusion of sequestered (biogenic) carbon • Assumptions about end of life treatment
Mineral Wool Insulation	• Production process – i.e. whether glass or stone based mineral wool
Polyurethane Insulation	• Assumptions about end of life treatment
Aggregates	• Production process – i.e. what the source or feedstock material for the aggregate is
Cement	• Choice of level of data aggregation: are data averaged for all blended cements or only for OPC

Supplementary cementitious material (SCM)	- Method used to allocate emissions from the production process for which the SCM is a co-product
Concrete	- Assumptions about end of life treatment

9.4.2 Effects of Uncertainty on Comparative Embodied Carbon Assessments

The results of the uncertainty assessment for these materials were then used to assess the effects of uncertainty on the comparison of embodied carbon for alternative materials. Three case studies, each representing the comparison of one standard material with an alternative material perceived to have lower embodied carbon, were assessed in this way. The three material comparison case studies were chosen because they represent alternative materials that have been used by Sainsbury's in previous schemes including the case study buildings used in Chapter 4 of this research to test and demonstrate the use of BIM to facilitate embodied carbon assessments. The data for the material comparison case studies were taken from these building case studies in Chapter 4.

Case Study 7-1 – Steel vs. Glulam timber for the structural frame
Case Study 7-2 – Composite steel deck vs. insulated timber cassettes for the roof
Case Study 7-3 – Standard concrete using Portland cement vs. low carbon concrete using a blend of Portland cement and PFA.

The results showed that the levels of uncertainty are so great that for all three comparisons, the low carbon alternative could, under certain combinations of assumptions or conditions, actually result in higher embodied carbon emissions than the standard material. The results are summarised in Table 9-3.

Table 9-3: Uncertainty ranges for the estimated change in embodied carbon achievable by replacing a standard material for a low carbon alternative in the design of a supermarket

		Uncertainty range of embodied carbon savings					
		Scenario Uncertainty Only (tCO_2e)		**Scenario and Statistical Uncertainty (tCO_2e)**		**Percentage Reduction**	
Design stage material change:		Max	Min	Max	Min	Max	Min
Glulam timber in place of steel for structural frame		50	-26.5	59	-38	170%	-160%
Insulated timber cassettes in place of composite steel deck for roof		766	-341	1066	-532	150%	-101
Low carbon concrete in place of standard concrete (100% Portland cement)	20% PFA	127	-45.5	n/a	n/a	37%	-16%
	50% GGBS	200.5	-167.5	n/a	n/a	59%	-60%

- Positive values represent an estimated saving achieved by implementing the material replacement described
- Negative values indicate an estimated increase in embodied carbon by implementing the replacement
- The figures for the steel vs. glulam comparison are based on a section of frame covering a floor area of 24m x 18m and 7m to underside of beams.
- The other comparisons are for an entire supermarket of 11,330 m2
- PFA = pulverised fly ash, GGBS = Ground granulated blastfurnace slag
- n/a = not assessed

These results show that the uncertainty in embodied carbon factors of materials can introduce risk to embodied carbon reduction initiatives. There is environmental risk since estimated savings may not be realised and embodied carbon may even increase as a result of a particular initiative. For businesses like Sainsbury's that may wish to evaluate the cost effectiveness of several alternative carbon mitigation initiatives, this uncertainty can also introduce financial risk. Where embodied carbon mitigation strategies incur capital costs, the business is likely to want to evaluate which strategies deliver the greatest reduction for the least expenditure. Uncertainty in the estimated savings introduces the risk that this evaluation of the cost of abatement is incorrect.

9.4.3 Approaches to Mitigating Sources of Scenario Uncertainty

The scenario uncertainties identified for each material assessed are due to different methodological choices or assumptions made when estimating the embodied carbon factor of the material. For each material, particular assumptions or choices of methods were shown to have a greater effect on the carbon factor than others. With reference to these key sources of uncertainty, different approaches that Sainsbury's could take to make a certain combination of assumptions or choices more reasonable or defensible were discussed in section 8.2.6. In this way, the plausibility or likelihood of alternative scenarios is reduced and so this can be considered as a strategy or approach to reduce or mitigate these sources of scenario uncertainty and hence also the risks that they introduce. The key conclusions of this discussion are summarised in Table 9-4.

Table 9-4: Strategies to mitigate scenario uncertainties for the five common construction materials.

Material	Key Source of Scenario Uncertainty	Approach to mitigate scenario uncertainty
Steel	Level of data aggregation: Industry averages carbon factor vs. carbon factors for specific production routes	Undertake to promote the use of alternatives to steel for applications (such as those requiring sheet steel) where high recycled content steel is not available. It is argued that this approach can negate the claim that specifying high recycled content steel has no net benefit due to the constrained market for scrap steel. For further details see section 8.2.6.1
Timber	Methodological choice: Credit for sequestration included or excluded Assumption: End of life treatment of timber	The use of sustainably certified timber is argued here and elsewhere (Darby, 2014) to provide a reasonable justification for giving credit for sequestered carbon in timber. The effect on embodied carbon factors for timber of different end of life scenarios is confused by the requirement under EN 15804 (British Standards Institution, 2014a), for sequestered or biogenic carbon to be shown as an emission at this stage even if the timber is reused or recycled. Because of this, the results produced here appear to suggest that sending the timber to land fill could result in the lowest emissions, provided the timber is not ground or chipped. However, this result is misleading and contradicts the waste hierarchy approach to prioritising different waste treatment routes (European Union, 2008).

Material	Key Source of Scenario Uncertainty	Approach to mitigate scenario uncertainty
Insulants	Assumption: Type of mineral wool – glass or stone wool	The embodied carbon factor of glass wool is significantly lower than stone wool due to the high recycled content of glass wool. By ensuring that whenever mineral wool is required, glass based wool is specified, this source of scenario uncertainty can be eliminated.
Cement and Concrete	Methodological choice: Allocation method used to estimate carbon factors for SCMs	The research found that there continues to be debate and disagreement amongst industry actors and researchers as to the best approach to allocating emissions to PFA and GGBS. Moreover there is evidence to suggest UK supplies of GGBS may be constrained. It was thus concluded here that, whilst these materials should still be used as much as possible to replace cement, the industry should not rely on these but should look to develop alternative ways to reduce the embodied carbon of cement. Sainsbury's should evaluate the savings achievable against a baseline calculated using data for UK average cements rather than 100% OPC to ensure estimated savings can be considered to be additional. Even then, estimated savings should be considered to be subject to high levels of uncertainty.

9.4.4 The Role of Standards in Mitigating Uncertainty

The introduction and use of standards can be considered to be an approach to dealing with uncertainty (Heijungs & Huijbregts, 2004). It is an approach that seeks to eliminate the effects of uncertainty by adopting a common methodology and assumptions. Supporters of the new European standards for life cycle assessment of buildings, EN 15978 (British Standards Institution, 2011a), and construction products, EN 15804 (British Standards Institution, 2014a), argue that results, including those of embodied carbon assessments, will be more directly comparable when these standards are consistently applied (Ilomäki, 2016; Moncaster & Symons, 2013)

Whilst this research does not refute this view in general terms, the results show that for certain specific and important issues, the standards do not provide the necessary clarity to ensure consistent methods are adopted. In particular, EN 15804 compliant EPDs have been produced by the steel industry and by the concrete industry, which appear to use different allocation methods for the GGBS. Similarly some EPDs are produced by industry bodies and represent aggregated data for the whole industry, whilst other EPDs for the same materials are specific to a particular supplier. The level of data aggregation was shown in this research to be an important source of uncertainty for steel, aggregates and cement. More specific guidance is needed in the standards on how these issues are addressed if they are to provide the desired levels of comparability between compliant studies.

9.5 Recommendations for Further Research

The outcomes of this work indicate a number of further lines of enquiry which could lead to meaningful progress in the wider implementation of embodied carbon assessments of buildings and improve the reliability of results. The following are recommended themes for further research:

- **Investigate and develop new methods to automate the linking of BIM objects and embodied carbon data.**

  In particular research in this area should explore how to overcome the current static nature of EPDs to make them machine-readable.

- **Improve the availability of carbon data for the construction stage of the building life cycle**

  The availability of data is generally much poorer for the life cycle stages between "gate and grave", i.e. post manufacture and pre disposal. Of these, the results here suggest that the construction stage has the highest impacts. Yet moves towards increased use of EPDs have failed to improve availability of carbon data for this stage because the EPD producers are not responsible for these emissions. There is a need for empirical research to improve the availability of this data. Moreover, given the popularity of EPDs, investigation into meaningful ways to allocate construction site emissions to specific materials used could allow more EPD producers to include this life cycle stage in their assessments.

- **Conduct further research into the statistical sources of uncertainty that affect embodied carbon factors.**

  Improved methods of expert elicitation are needed to allow more robust estimates of uncertainty ranges for the carbon factors (or other environmental impact indicators) of materials. In particular the results of this research suggest that it may be advantageous to conduct elicitations for some of the key input variables used to estimate carbon factors rather than for the carbon factors themselves. This requires further analysis to identify which key variables to include in such an elicitation and the level to which inputs should be disaggregated. In the longer term, the priority should be to replace estimates of statistical uncertainty based on expert judgement with values derived from empirical data. This requires further empirical work to generate the necessary data. The focus for this should be on key materials such as concrete and steel, which represent a large proportion of embodied carbon emissions for the sector.

- **Investigate techniques to apply the methods developed here to assess uncertainty for a whole building**

  The scenario assessment technique applied here works well when assessing small numbers of materials. Yet it starts to become more impractical as more materials are included because the number of scenarios increases significantly and becomes unmanageable. Further research initiatives to develop the method should look for ways to assess the impacts of scenario level uncertainties using computer simulations so that their effects on the embodied carbon of whole buildings may be evaluated

9.6 Recommendations to Industry

Throughout the course of this research, feedback on the results and outcomes has been provided to Sainsbury's through informal discussions, and formal meetings and presentations. The following key points represent a synthesis of the recommendations made to Sainsbury's which could be relevant to practitioners in low carbon design of supermarkets and other similar types of commercial buildings as well as to the wider construction industry and construction materials supply chain.

- Improved accuracy of BIM models, with a particular focus on the areas highlighted in section 9.1 above, is crucial to increasing the level of automation achievable for embodied carbon assessments.
- Using the BIM embodied carbon calculator to assess the embodied carbon of a range of different typical configurations of store layout would allow Sainsbury's to develop benchmarks for these

common typologies. These could be used to evaluate the embodied carbon impacts of proposed new stores in the earliest stages of design.

- Similarly, increasing the level of standardisation in supermarket design could allow for the earlier creation of relatively detailed BIM models with more information on material specifications. This would allow detailed embodied carbon assessments to be undertaken earlier in the design process.
- Taking account of uncertainty increases the complexity of the embodied carbon assessments but is important to fully understand the potential environmental and financial risks involved in decision making with respect to embodied carbon mitigation.
- The sources of uncertainty with the greatest impact on carbon factors for key materials used in supermarket construction are related to assumptions and choices made when calculating those carbon factors. In particular, for steel, concrete and timber, three of the most important materials in terms of embodied impacts of supermarkets, the level of data aggregation (for example, whether carbon factors are industry average figures or supplier specific), the assumptions about end of life treatment and the way emissions are allocated between multiple products from the same process are typically the most important issues driving uncertainty.
- Environmental product declarations represent a promising source of material carbon factors for use in building assessments. Their data quality is judged by most experts consulted, to be higher than carbon factors from other sources. However, there are limitations to the standards which underpin EPDs. The two key limitations identified through this research relate to the approach taken to construction site emissions and the lack of clear guidance in regard to allocation methods and data aggregation.
- Typically, EPD are produced by product manufacturers or their industry bodies and as such many do not contain data on construction site emissions. Businesses like Sainsbury’s that have ongoing annual construction programmes should implement schemes to monitor emissions from their construction sites in order to fill this gap in the data.
- Users of EPD should ensure that they identify and record the allocation methods used and the level that data are aggregated. EPDs that do not make this information clear should be avoided or used with caution. The decision trees developed as part of this research could provide a useful way of clearly communicating the methodological choices and assumptions made in producing each EPD. Moreover this would allow more users of EPD to take account of these important sources of uncertainty in their embodied carbon and life cycle assessments.

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Appendices

Appendix A: Summary of Sainsbury’s prior work on embodied carbon

Table A-1: Summary of life cycle carbon assessments of buildings commissioned by Sainsbury's between 2007-2011

<table>
<tr><th>Building</th><th>Report No.</th><th>Year</th><th>Scope</th><th>Assumed Life cycle</th><th>Data Sources</th></tr>
<tr><td>Sainsbury’s Oakley
(dCarbon8, 2007)</td><td>1</td><td>2007</td><td>Cradle to Grave
Structure, envelope, fit-out and external works</td><td>30 years</td><td>Resource Quants:
Primary site data (materials)
Literature (construction and demolition energy)
Emissions Factors:
ICE</td></tr>
<tr><td colspan="6">Notes
• The report claims to cover all 6 Kyoto greenhouse gases and report CO_2e. Yet the only source cited is ICE which, at the time, only provided CO_2 emissions factors.
• Further, the report claims that these emissions factors are from cradle to site but ICE itself states that factors are cradle to gate only. Therefore, transport to site appears to have been omitted.
• No data was collected on contractor’s energy consumption and emissions from site activities are simply assumed to equate to 10% of the total.
• Demolition emissions assumed to be 2% of total based on Amato et al. (Amato, Brimacombe, & Howard, 1996) and Cole and Kernan (1996)</td></tr>
<tr><td>Sainsbury’s Dartmouth
(dCarbon8, 2008)</td><td>2</td><td>2008</td><td>Cradle to Grave
Structure, envelope, fit-out and external works</td><td>30 years</td><td>Resource Quants:
Primary site data (materials)
Prior studies (some materials & construction energy)
Literature (demolition energy)
Emissions Factors:
ICE, SimaPro, Ecoinvent</td></tr>
<tr><td colspan="6">Notes
• The report claims to cover all 6 Kyoto greenhouse gases and report CO_2e. Data is mainly drawn from ICE which is only CO_2. The report says that factors to convert CO_2 to CO_2e were calculated using SimaPro but these are not provided.
• A small amount of data was sourced from Ecoinvent but the report does not explicitly state for which materials
• Data was collected on contractor’s energy consumption anD included employee travel to and from site.
• Material quantity data based on actual quantities delivered. Where this was not available secondary data was used from the previous study at Oakley on a pro-rata basis using floor area. The report does not state which data was sourced in this manner.</td></tr>
</table>

<table>
<tr><td colspan="6">• Demolition emissions assumed to be 2% of total based on Amato et al. (Amato, Brimacombe, & Howard, 1996) and Cole and Kernan (1996)</td></tr>
<tr><td>Sainsbury's Gloucester Quays
(dCarbon8, 2009)</td><td>3</td><td>2009</td><td>Cradle to Grave
Structure, envelope, fit-out and external works for supermarket and petrol station</td><td>30 years</td><td>Resource Quants:
Primary site data (materials & construction energy)
Design data (some materials)
Prior studies (some materials)
Literature (demolition energy)
Emissions Factors:
ICE, Ecoinvent</td></tr>
<tr><td colspan="6">Notes
• The report claims to cover all 6 Kyoto greenhouse gases and report CO_2e. Data is mainly drawn from ICE, which is only CO_2. The report says that factors to convert CO_2 to CO_2e were calculated using SimaPro.
• Some emissions factors sourced from EcoInvent but the report does not state for which materials.
• Primary data collected on contractor's energy consumption, including employee travel to and from site.
• Materials quantities based on actual deliveries. Where this was not available, bill of quantities (BOQ) data was used. Where the BOQ didn't provide adequate data, secondary data was used from the previous study at Oakley on a pro-rata basis using floor area. The report does list which data was sourced in this manner.
• Demolition emissions assumed to be 2% of total based on Amato et al. (Amato, Brimacombe, & Howard, 1996) and Cole and Kernan (1996)</td></tr>
<tr><td>Sainsbury's Westhoughton
(dCarbon8, 2010)</td><td>4</td><td>2010</td><td>Cradle to Grave</td><td>60 years</td><td>Resource Quants:
Primary site data (materials)
Design data (some materials)
Prior studies (some materials)
Literature (transport, construction & demolition energy)
Emissions Factors:
ICE, Ecoinvent</td></tr>
<tr><td colspan="6">Notes
• The report claims to cover all 6 Kyoto greenhouse gases and report CO_2e. Data is mainly drawn from ICE, which is only CO_2. The report says that factors to convert CO_2 to CO_2e were calculated using SimaPro.
• Some emissions factors sourced from EcoInvent but the report does not state for which materials.
• Primary data collected on contractor's energy consumption, including employee travel to and from site.</td></tr>
</table>

• Materials quantities based on actual deliveries. Where this was not available, bill of quantities (BOQ) data was used. Where the BOQ didn't provide adequate data, secondary data was used from the previous study at Oakley on a pro-rata basis using floor area. The report does list which data was sourced in this manner. • Demolition emissions assumed to be 2% of total based on Amato et al. **(Amato, Brimacombe, & Howard, 1996)** and Cole and Kernan **(1996)**					
Sainsbury's 30k Model Store **(dCarbon8, 2010)**	4	2010	Cradle to Grave	60 years	As above

Sainsbury's Dawlish **(Deloitte, 2010)**	5	2011	Cradle to Grave	Unknown	**Resource Quants:** Primary site data (materials) Prior studies (some materials) **Emissions Factors:** Not referenced
Notes • The study was not presented in full report format as the others but as a set of slides and hence much less detail is available. • Emissions reported as CO_2e but no information on how this is calculated. • No information provided as to sources of emissions factors used. • No information about assumptions made					

Appendix B: Systematic Literature Review Results

Table B-1: Results of a systematic review of 60 peer reviewed studies of LCA, embodied carbon assessments (ECA) and life cycle carbon assessment (LCCA) of buildings and building components

			Study Type		Search Terms[9]					
Author	**Year**	**Title**	**Building (A) / Component (B)**	**LCA (A) / ECA/LCCA (B)**	**Uncertain***	**Sensitiv***	**Data Quality**	**Error**	**Varia***	**Includes Uncertainty Assessment**
Acquaye et al.	2011	Embodied emissions abatement—A policy assessment using stochastic analysis	A	B	•		•	•	•	•
Acquaye et al.	2011	Stochastic hybrid embodied CO2-eq analysis: An application to the Irish apartment building sector	A	B	•	•		•	•	•
Aktas & Bilec	2012	Impact of lifetime on US residential building LCA results	A	A	•	•		•	•	•
Aranda-Uson et al.	2013	Phase change material applications in buildings: An environmental assessment for some Spanish climate severities	B	A						
Arena & Rosa	2003	Life cycle assessment of energy and environmental implications of the implementation of conservation technologies in school buildings in Mendoza—Argentina	A	A						
Asdrubali et al.	2013	Life cycle analysis in the construction sector: guiding the optimization of conventional Italian buildings	A	A	•	•	•	•		
Asif et al.	2005	Life cycle assessment: A case study of a dwelling home in Scotland	A	A						
Aye	2012	Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules	A	B	•			•	•	
Babaizadeh and Hassan	2013	Life cycle assessment of nano-sized titanium dioxide coating on residential windows	B	A		•				
Blengini	2009	Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy	A	A	•	•				•
Bribian et al.	2011	Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency potential	B	A			•		•	

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[9] Search terms included variants such as singular/plural or nouns/adjectives etc.
• = relevant instances of the search term found in the study
◦ = search term found in the text but not used in relation to uncertainty

			Study Type		Search Terms[9]					
Author	Year	Title	Building (A) / Component (B)	LCA (A) / ECA/LCCA (B)	Uncertain*	Sensitiv*	Data Quality	Error	Varia*	Includes Uncertainty Assessment
Castell et al.	2013	Life Cycle Assessment of alveolar brick construction system incorporating phase change materials (PCMs)	B	A				◦	◦	
Cellura et al.	2011	Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: The case study of an Italian tile	B	A	•	•	•	•	•	•
Citherlet & Defaux	2007	Energy and environmental comparison of three variants of a family house during its whole life span	A	A					◦	
De Gracia et al.	2010	Life Cycle Assessment of the inclusion of phase change materials (PCM) in experimental buildings	B	A						
Esin	2007	A study regarding the environmental impact analysis of the building materials production process (in Turkey)	B	A						
Fay et al.	2010	Life-cycle energy analysis of buildings: a case study	A	B				•	•	
Gong et al.	2012	Life Cycle Energy Consumption and Carbon Dioxide Emission of Residential Building Designs in Beijing	A	B			•			
Gustavsson & Joelsson	2010	Life cycle primary energy analysis of residential buildings	A	B		•		•	◦	•
Huberman & Pearlmutter	2008	A life-cycle energy analysis of building materials in the Negev desert	A	B		•			◦	
Huijbregts et al.	2003	Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling	B	A	•	•		•	•	
Joensson et al.	1997	Life Cycle Assessment of Flooring Materials: Case Study	B	A					•	
Kellenberger and Althaus	2009	Relevance of simplifications in LCA of building components	A	A						
Keoleian et al.	2000	Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House	A	A						
Kofoworola & Gheewala	2008	Environmental life cycle assessment of a commercial office building in Thailand	A	A				◦	◦	
Kofoworola & Gheewala	2009	Life cycle energy assessment of a typical office building in Thailand	A	B			•		•	
Koroneos and Dompros	2007	Environmental assessment of brick production in Greece	B	A						
Kua & Wong	2012	Analysing the life cycle greenhouse gas emission and energy consumption of a multi-storied commercial building in Singapore from an extended system boundary perspective	A	B	•	•				•

			Study Type		Search Terms[9]					
Author	**Year**	**Title**	**Building (A) / Component (B)**	**LCA (A) / ECA/LCCA (B)**	**Uncertain***	**Sensitiv***	**Data Quality**	**Error**	**Varia***	**Includes Uncertainty Assessment**
Menoufi et al.	2012	Evaluation of the environmental impact of experimental cubicles using Life Cycle Assessment: A highlight on the manufacturing phase	B	A						
Menoufi et al.	2013	Life cycle assessment of experimental cubicles including PCM manufactured from natural resources (esters): a theoretical study	B	A						
Mithraratne & Vale	2004	Life cycle analysis model for New Zealand houses	A	A						
Monahan and Powell	2011	An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework	A	B			•			
Mosteiro-Romero et al.	2014	Relative importance of electricity sources and construction practices in residential buildings: A Swiss-US comparison of energy related life-cycle impacts	A	A	•	•				•
Nassen et al.	2012	Concrete vs. wood in buildings – An energy system approach	A	B		•				•
Nicoletti et al.	2002	Comparative Life Cycle Assessment of flooring materials: ceramic versus marble tiles	B	A						
Norman et al.	2006	Comparing high and low residential density: life-cycle analysis of energy use and greenhouse gas emissions	A	A		•		•		
Norris and Yost	2002	A Transparent, Interactive Software Environment for Communicating Life-Cycle Assessment Results	B	A	•	•		•	•	•
Peuportier	2001	Life cycle assessment applied to the comparative evaluation of single family houses in the French context	A	A	•	•		•	•	•
Peuportier et al.	2013	Eco-design of buildings using thermal simulation and life cycle assessment	A	A	•	•			•	•
Proietti et al.	2013	Life Cycle Assessment of a passive house in a seismic temperate zone	A	A			•			
Radhi and Sharples	2013	Global warming implications of facade parameters: A life cycle assessment of residential buildings in Bahrain	B	A						
Rincon et al.	2013	Evaluation of the environmental impact of experimental buildings with different constructive systems using Material Flow Analysis and Life Cycle Assessment	B	A						
Scheuer et al.	2003	Life cycle energy and environmental performance of a new university building: modeling challenges and design implications	A	B					•	
Shukla et al.	2009	Embodied energy analysis of adobe house	A	B						

			Study Type		Search Terms[9]					
Author	**Year**	**Title**	**Building (A) / Component (B)**	**LCA (A) / ECA/LCCA (B)**	**Uncertain***	**Sensitiv***	**Data Quality**	**Error**	**Varia***	**Includes Uncertainty Assessment**
Suzuki and Oka	1998	Estimation of life cycle energy consumption and CO2 emission of office buildings in Japan	A	B				•		
Thiel et al.	2013	A materials life cycle assessment of a net-zero energy building	A	A						
Thormark	2002	A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential	A	B						
Treloar et al.	2000	Analysing the life-cycle energy of an Australian residential building and its householders	A	B				•	•	
Treloar et al.	2001	Building materials selection: greenhouse strategies for built facilities	A	B				•	•	
Utama & Gheewala	2008	Life cycle energy of single landed houses in Indonesia	A	B		◦				
Van den Heede and De Belie	2012	Environmental impact and life cycle assessment (LCA) of traditional and ‘green’ concretes: Literature review and theoretical calculations	B	A	•	•	•		•	
van der Lugt et al.	2006	An environmental, economic and practical assessment of bamboo as a building material for supporting structures	B	A	•		•			
Van Geem and Marceau	2006	Comparison of the life cycle assessments of an insulating concrete form house and a wood frame house	A	A	•	•	•	•	•	
Venkatarama Reddy and Jagadish	2003	Embodied energy of common and alternative building materials and technologies	B	B						
Vieira and Horvath		Assessing the End-of-Life Impacts of Buildings	A	A	•	•	•		•	•
Winter & Hestnes	1999	Solar Versus Green: The Analysis of a Norwegian Row House	A	B						
Wu et al.	2005	Study of the environmental impacts based on the green tax—applied to several types of building materials	B	A						
Xing et al.	2008	Inventory analysis of LCA on steel- and concrete-construction office buildings	A	A						
Yohanis & Norton	2002	Life-cycle operational and embodied energy for a generic single-storey office building in the UK	A	B					•	
Zimmermann et al.	2005	Benchmarks for sustainable construction: A contribution to develop a standard	B	A						

Appendix C: Carbon Factors in the Embodied Carbon Calculation Spreadsheet

Table C-1: Carbon factors for each life cycle module (EN 15804) and the source (see Table C-2 for references)

Category	Material	Density	Units[10]	A1-3	A4	A5	B1-4	B5	C1-4	D	Source
Aggregate	Aggregate - Custom	2240	kg	0.000			0.000		0.000		1
Aggregate	Aggregate - General	2240	kg	0.005			0.000		0.000		1
Aggregate	Sand	2240	kg	0.005			0.000		0.000		1
Aggregate	Shingle (CO2)		kg	0.300			0.000		0.000		1
Aggregate	Soil - rammed	2050	kg	0.024			0.000		0.000		1
Aggregate	Vermiculite - Expanded (CO2)		kg	0.520			0.000		0.000		1
Aggregate	Vermiculite - Natural (CO2)		kg	0.032			0.000		0.000		1
Asphalt	Asphalt - % binder content	2300	kg	0.066			0.000		0.000		1
Asphalt	Asphalt - 5% binder content	2300	kg	0.071			0.000		0.000		1
Asphalt	Asphalt - 6% binder content	2300	kg	0.076			0.000		0.000		1
Asphalt	Asphalt - 7% binder content	2300	kg	0.081			0.000		0.000		1
Asphalt	Asphalt - 8% binder content	2300	kg	0.086			0.000		0.000		1
Asphalt	Asphalt - Custom	2300	kg	0.000			0.000		0.000		1
Blockwork	Concrete Block - 10 MPa	2100	kg	0.078			0.000		0.010	-0.006	3
Blockwork	Concrete Block - 8 Mpa	2100	kg	0.063			0.000		0.010	-0.006	3
Blockwork	Concrete Block - unspecified	2100	kg	0.090			0.000		0.010	-0.006	3
Blockwork	Concrete Block -12 MPa	2100	kg	0.088			0.000		0.010	-0.006	3
Blockwork	Concrete Block -13 MPa	2100	kg	0.107			0.000		0.010	-0.006	3
Brick	Brick - Custom	2080	kg	0.158			0.000		0.000		1
Brick	Brick - Brick EPD (BDA)	1550	kg	0.158			0.000		0.000	-0.002	4
Brick	Brick (by mass)	2080	kg	0.240			0.000		0.000		1
Brick	Brick (per 2.3kg brick)	1	ea	0.550			0.000		0.000		1
Cement	Cement - CEM II/A-V (max 20% PFA)	1860	kg	0.760			0.000		0.002		1,10

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[10] Indicates the base, or denominator, of the functional unit. All values are CO_2e unless otherwise indicated in the *Material* field

Category	Material	Density	Units[10]	A1-3	A4	A5	B1-4	B5	C1-4	D	Source
Cement	Cement - CEM II/A-V (min 6% PFA)	1860	kg	0.890			0.000		0.002		1,10
Cement	Cement - CEM II/B (max 80% GGBS)	1860	kg	0.260			0.000		0.002		1,10
Cement	Cement - CEM II/B (min 66% GGBS)	1860	kg	0.380			0.000		0.002		1,10
Cement	Cement - CEM II/B-S (max 35% GGBS)	1860	kg	0.650			0.000		0.002		1,10
Cement	Cement - CEM II/B-S (min 21% GGBS)	1860	kg	0.770			0.000		0.002		1,10
Cement	Cement - CEM II/B-V (max 35% PFA)	1860	kg	0.620			0.000		0.002		1,10
Cement	Cement - CEM II/B-V (min 21% PFA)	1860	kg	0.750			0.000		0.002		1,10
Cement	Cement - CEM III/A (max 65% GGBS)	1860	kg	0.390			0.000		0.002		1,10
Cement	Cement - CEM III/A (min 36% GGBS)	1860	kg	0.640			0.000		0.002		1,10
Cement	Cement - CEMI	1860	kg	0.950			0.000		0.002		1,10
Ceramics	Ceramics - Custom	2000	kg	0.000			0.000		0.002		1,10
Ceramics	Ceramics - Fittings	2000	kg	1.140			0.000		0.002		1,10
Ceramics	Ceramics - General	2000	kg	0.700			0.000		0.002		1,10
Ceramics	Ceramics - Sanitary Products	2000	kg	1.610			0.000		0.002		1,10
Ceramics	Ceramics - Tiles and Cladding Panels	2000	kg	0.780			0.000		0.002		1,10
Concrete	Concrete - 16/20 Mpa	2200	kg	0.100			0.000		0.012	-0.031	1,10
Concrete	Concrete - 20/25 MPa	2200	kg	0.107			0.000		0.012	-0.031	1,10
Concrete	Concrete - 25/30 MPa	2200	kg	0.113			0.000		0.012	-0.031	1,10
Concrete	Concrete - 28/35 MPa	2200	kg	0.120			0.000		0.012	-0.031	1,10
Concrete	Concrete - 32/40 MPa	2200	kg	0.132			0.000		0.012	-0.031	1,10
Concrete	Concrete - 40/50 MPa	2200	kg	0.151			0.000		0.012	-0.031	1,10
Concrete	Concrete - Custom	2200	kg	0.000			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 28/35 (15% GGBS)	2300	kg	0.119			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 28/35 (15% PFA)	2300	kg	0.138			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 28/35 (30% GGBS)	2300	kg	0.088			0.000		0.012	-0.031	1,10

Category	Material	Density	Units[10]	A1-3	A4	A5	B1-4	B5	C1-4	D	Source
Concrete	Concrete - RC 28/35 (30% PFA)	2300	kg	0.124			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 28/35 (CEM I)	2300	kg	0.148			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 30/37 (30% PFA)	2300	kg	0.170	0.003		0.000		0.007	-0.031	2
Concrete	Concrete - RC 30/37 (50% GGBS)	2300	kg	0.170	0.003		0.000		0.007	-0.031	2
Concrete	Concrete - RC 30/37 (CEM I)	2300	kg	0.200	0.003		0.000		0.008	-0.031	2
Concrete	Concrete - RC 32/40 (15% GGBS)	2300	kg	0.133			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 32/40 (15% PFA)	2300	kg	0.152			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 32/40 (30% PFA)	2301	kg	0.102			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 32/40 (30% GGBS)	2300	kg	0.100			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 32/40 (30% PFA)	2300	kg	0.136			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 32/40 (CEM I)	2300	kg	0.163			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 40/50 (15% GGBS)	2300	kg	0.153			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 40/50 (15% PFA)	2300	kg	0.174			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 40/50 (30% GGBS)	2300	kg	0.115			0.000		0.012	-0.031	1,10
Concrete	Concrete - RC 40/50 (30% PFA)	2300	kg	0.155			0.000		0.013	-0.031	2
Concrete	Concrete - RC 40/50 (CEM I)	2300	kg	0.188			0.000		0.012	-0.031	1,10
Concrete	Concrete - Very High GGBS Mix	2200	kg	0.050			0.000		0.012	-0.031	1,10
Glass	Glass - Custom	2500	kg	0.000			0.000		0.000		1,10
Glass	Primary Glass	2500	kg	0.910			0.000		0.000		1,10
Glass	Secondary Glass	2500	kg	0.590			0.000		0.000		1,10
Glass	Toughened Glass	2500	kg	1.350			0.000		0.000		1,10
Glass	Glazed Curtain Wall - EPD		m²	72.990			0.000		2.754	-24.300	9
Glass	Flat Glass - 4mm Pane EPD	2500	m²	10.680			0.000		0.026	-5.560	9
Glass	Flat Glass - 6mm Pane EPD	2500	m²	16.020			0.000		0.026	-8.340	9
Glass	Flat Glass - by volume EPD	2500	m³	2670.000			0.000		0.026	-1390.000	9
Insulation	Insulation - Fibreglass (CO2)	25	kg	1.350			0.000		0.000		1
Insulation	Insulation - Flax(CO2)	?	kg	1.700			0.000		0.000		1
Insulation	Insulation - General (CO2)	100	kg	1.860			0.000		0.000		1
Insulation	Insulation - Mineral wool	240	kg	1.280			0.000		0.000		1

Category	Material	Density	Units[10]	A1-3	A4	A5	B1-4	B5	C1-4	D	Source
Insulation	Insulation - Mineral wool EPD	45	kg	53.800	0.605		0.000		0.487		11
Insulation	Insulation - Polystyrene	32	kg	3.290			0.000		0.000		1
Insulation	Insulation - Polyurethane with mineral fleece facing - 120mm	31	kg	3.026	0.085	0.076	0.000		2.303	-1.081	12
Insulation	Insulation - Polyurethane	30	kg	4.260			0.000		0.000		1
Insulation	Insulation - Rockwool	100	kg	1.120			0.000		0.000		1
Metals	Aluminium - cast	2700	kg	9.220			0.000		0.000		1
Metals	Aluminium - Custom	2700	kg	0.000			0.000		0.000		1
Metals	Aluminium - extruded - oekobaudat	2700	kg	10.930			0.000		0.001	-8.457	8
Metals	Aluminium - extruded	2700	kg	9.080			0.000		0.000		1
Metals	Aluminium - general	2700	kg	9.160			0.000		0.000		1
Metals	Aluminium - rolled	2700	kg	9.180			0.000		0.000		1
Metals	Aluminium - rolled - oekobaudat	2700	kg	10.690			0.000		0.001	-8.457	8
Metals	Copper - Tube & Sheet	8600	kg	2.710			0.000		0.000		1
Miscellaneous	Lledo Rooflight	20	ea	182.000			0.000		0.000		1
Miscellaneous	Rooflight EPD	20	ea	78.624	2.880	68.112	221.069	0.000	61.661	-50.688	13
Miscellaneous	Mandolite (CO2)	?	kg	1.400			0.000		0.000		1
Miscellaneous	Refridge Cabinet 0800	130	ea	250.000			0.000		0.000		19
Miscellaneous	Refridge Cabinet 1250	200	ea	390.000			0.000		0.000		19
Miscellaneous	Refridge Cabinet 1800	300	ea	580.000			0.000		0.000		19
Miscellaneous	Refridge Cabinet 2400	400	ea	770.000			0.000		0.000		19
Miscellaneous	Refridge Cabinet 2600	430	ea	820.000			0.000		0.000		19
Miscellaneous	Rockspan - 100mm (kg/m^2)	20	m^2	43.550			0.000		0.000	-14.810	14
Miscellaneous	Rockspan - 125mm (kg/m^2)	22	m^2	46.240			0.000		0.000	-14.750	14
Miscellaneous	Rockspan - 150mm (kg/m^2)	25	m^2	48.920			0.000		0.000	-14.690	14
Miscellaneous	Rockspan - 175mm (kg/m^2)	27	m^2	51.610			0.000		0.000	-14.630	14
Miscellaneous	Rockspan - 75mm (kg/m^2)	17	m^2	40.860			0.000		0.000	-14.870	14
Mortar	Mortar (1:½:4½ Cement:Lime:Sand mix)	1600	kg	0.213			0.000		0.000		1
Mortar	Mortar (1:1:6 Cement:Lime:Sand mix)	1600	kg	0.174			0.000		0.000		1
Mortar	Mortar (1:2:9 Cement:Lime:Sand mix)	1600	kg	0.155			0.000		0.000		1
Mortar	Mortar (1:3 cement:sand mix)	1900	kg	0.221			0.000		0.000		1

Category	Material	Density	Units[10]	A1-3	A4	A5	B1-4	B5	C1-4	D	Source
Mortar	Mortar (1:4)	1900	kg	0.182			0.000		0.000		1
Mortar	Mortar (1:5)	1900	kg	0.156			0.000		0.000		1
Mortar	Mortar (1:6)	1900	kg	0.136			0.000		0.000		1
Paint	Paint - Custom	2100	kg	0.000			0.000		0.000		1
Paint	Paint - Double Coat (per m²)	2100	m²	0.064			0.000		0.000		1
Paint	Paint - general	2100	m²	2.910			0.000		0.000		1
Paint	Paint - Single Coat (per m²)	2100	m²	0.437			0.000		0.000		1
Paint	Paint - Solventborne	2100	kg	3.760			0.000		0.000		1
Paint	Paint - Triple Coat (per m²)	2100	m²	1.311			0.000		0.000		1
Paint	Paint - Waterborne	2100	kg	2.540			0.000		0.000		1
Paint	Wood stain/Varnish (CO2)	2100	kg	5.350			0.000		0.000		1
Plaster	Plaster - Custom	1120	kg	0.000			0.000		0.000		1
Plaster	Plaster - General (Gypsum)	1120	kg	0.130			0.000		0.000		1
Plaster	Plasterboard	950	kg	0.390			0.000		0.000		1
Plaster	Gyproc WallBoard	668	m²	2.200	0.000	0.710	0.000	0.000	0.019		15
Plastics	Plastics - HDPE Pipe	970	kg	2.520			0.000		0.000		1
Plastics	Plastics - HDPE Resin	970	kg	1.930			0.000		0.000		1
Plastics	Plastics - High Impact Polystyrene	1050	kg	3.420			0.000		0.000		1
Plastics	Plastics - Polyurethane Rigid Foam	1200	kg	4.260			0.000		0.000		1
Plastics	Plastics - PVC General	1330	kg	3.100			0.000		0.000		1
Plastics	Plastics - PVC Injection Moulding	1330	kg	3.300			0.000		0.000		1
Plastics	Plastics - PVC Pipe	1330	kg	3.230			0.000		0.000		1
Plastics	Plastics - Thermoformed Expanded Polystyrene	35	kg	4.390			0.000		0.000		1
Plastics	Plastics - UPVC Film	1330	kg	3.160			0.000		0.000		1
Plastics	Vinyl flooring	1300	kg	3.190			0.000		0.000		1
Renewables	PV Panel - Generic	12	m²	242.000			0.000		0.000		1
Rubber	Rubber	1500	kg	2.850			0.000		0.000		1
Rubber	Rubber - Custom	1500	kg	0.000			0.000		0.000		1
Steel	Steel - Bar & rod	7850	kg	1.400			0.000		0.000		1
Steel	Steel - Coil (Sheet)	7850	kg	1.380			0.000		0.000		1
Steel	Steel - Coil (Sheet) - Darby	7850	kg	4.125			0.000		0.000	-1.394	16
Steel	Steel - Coil (Sheet) - Oekobaudat	7850	kg	2.162			0.000		0.001	-1.394	8

Category	Material	Density	Units[10]	A1-3	A4	A5	B1-4	B5	C1-4	D	Source
Steel	Steel - Coil (Sheet), Galvanised	7850	kg	1.540			0.000		0.004		1
Steel	Steel - Decking	7850	kg	2.538	0.024		0.000		0.060	-1.380	3
Steel	Steel - Decking - IFPS EPD 35mm	7	m²	16.500			0.000		0.010	-9.620	17
Steel	Steel - Folded Profile IFPS EPD	8	m²	19.100			0.000		0.010	-11.200	17
Steel	Steel - Engineering steel - Recycled	7850	kg	0.720			0.000		0.000		1
Steel	Steel - General	7850	kg	1.460			0.000		0.000		1
Steel	Steel - Light steel framing	7850	kg	2.538	0.024		0.000		0.060	-1.450	3
Steel	Steel - Pipe	7850	kg	1.450			0.000		0.000		1
Steel	Steel - Plate	7850	kg	1.660			0.000		0.000		1
Steel	Steel - Section	7850	kg	1.530			0.000		0.000		1
Steel	Steel - Stainless (CO2)	7850	kg	6.145			0.000		0.000		1
Steel	Steel - structural hollow section (hot rolled) incl. fabrication	7850	kg	2.538	0.024		0.000		0.060	-1.450	2,3
Steel	Steel - Structural section incl fabrication	7850	kg	2.006	0.013		0.000		0.060	-0.959	3
Steel	Steel - Wire - Virgin	7850	kg	3.020			0.000		0.000		1
Terrazzo	Terrazzo Tiles (CO2)	2100	kg	0.118			0.000		0.000		1
Timber	Straw (CO2)	??	kg	0.010			0.000		0.000		1
Timber	Timber - Custom	800	kg	0.000			0.000		0.000		1
Timber	Timber - General	720	kg	0.720			0.000		0.000		1
Timber	Timber - GlueLam	508	m³	-645.730			0.000		819.279	-372.400	7
Timber	Timber - Hardboard	1000	kg	1.090			0.000		0.000		1
Timber	Timber - Laminated Veneer Lumber	??	kg	0.650			0.000		5.612		1,7
Timber	Timber - MDF	??	kg	0.740			0.000		0.000		1
Timber	Timber - OSB sustainably sourced	600	m³	-565.230			0.000		977.567	-456.000	7
Timber	Timber - OSB	680	kg	0.990			0.000		0.000		1
Timber	Timber - Particle Board	750	kg	0.860			0.000		0.000		1
Timber	Timber - Plywood	700	kg	1.100			0.000		0.000		1
Timber	Timber - Sawn Hardwood	800	kg	0.870			0.000		0.000		1
Timber	Timber - Sawn Softwood	630	kg	-679.000	22.500		0.000		798.000	-366.000	7
	Timber - I-Beam	3	m	-418.707	12.576		0.000		675.800	-493.350	18

Table C-2: References for the carbon factors in Table C-1

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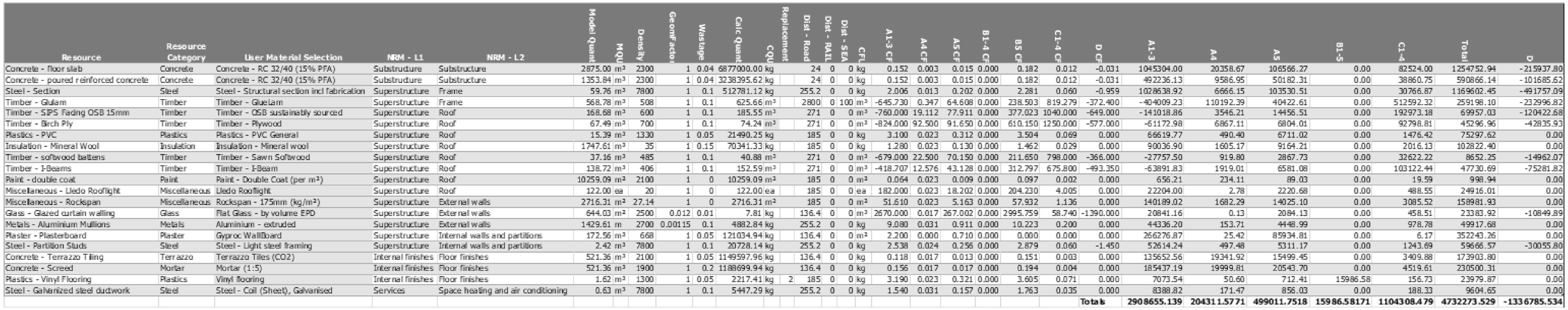
Appendix D: Case Study 4-1 – 60k Model Store – Quantity and Carbon Factor Data

Resource	Resource Category	User Material Selection	NRM - L1	NRM - L2	Model Quant	MQU	Density	GeomFactor	Wastage	Calc Quant	CQU	Replacement	Dist - Road	Dist - RAIL	Dist - SEA	CFU	A1-3 CF	A4 CF	A5 CF	B1-4 CF	B5 CF	C1-4 CF	D CF	A1-3	A4	A5	B1-5	C1-4	Total A-C	D
Blockwork - 215mm Blockwork	Blockwork	Concrete Block -13 MPa	Superstructure	Internal walls and partitions	18.050	m^3	2100	1	0.2	45484.76	kg	0	136.4	0	0	kg	0.107	0.016	0.012	0.000	0.145	0.010	-0.006	4866.87	705.04	557.19	0.00	468.49	6597.59	-259.26
Ceramics - 6mm Tile - single sided	Ceramics	Ceramics - Tiles and Cladding Panels	Internal finishes	Wall finishes	3.737	m^3	2000	1	0.08	8071.63	kg	0	136.4	0	0	kg	0.780	0.016	0.080	0.000	0.877	0.002	0.000	6295.87	125.11	642.10	0.00	16.14	7079.23	0.00
Concrete - floor slab	Concrete	Concrete - RC 32/40 (CEM I)	Substructure	Substructure	1631.073	m^3	2300	1	0.04	3901525.64	kg	0	24	0	0	kg	0.163	0.003	0.017	0.000	0.194	0.012	-0.031	635841.82	10640.86	64648.27	0.00	46818.31	757949.26	-122507.91
Concrete - poured reinforced concrete	Concrete	Concrete - RC 32/40 (CEM I)	Substructure	Substructure	931.346	m^3	2300	1	0.04	2227780.61	kg	0	24	0	0	kg	0.163	0.003	0.017	0.000	0.194	0.012	-0.031	363067.22	6075.96	36914.32	0.00	26733.37	432790.87	-69952.31
Glass - Glazed curtain walling	Glass	Flat Glass - 6mm Pane EPD	Superstructure	External walls	620.213	m^2	2500	2	0.01	1252.83	m^2	0	136.4	0	0	m^2	16.020	0.016	1.604	0.000	17.665	0.026	-8.340	20070.35	48548.74	2008.98	0.00	32.32	70660.39	-10448.61
Insulation - cold room panels	Insulation	Insulation - Polyurethane	Fittings, furnishings and equipment	Fittings, furnishings and equipment	80.298	m^3	30	1	0.15	2770.27	kg	1	185	0	0	kg	4.260	0.021	0.428	0.000	4.803	0.094	0.000	11801.34	58.24	1185.96	13306.45	260.91	26612.90	0.00
Insulation - PIR	Insulation	Insulation - Polyurethane	Superstructure	Roof	1076.373	m^3	30	1	0.15	37134.85	kg	0	185	0	0	kg	4.260	0.021	0.428	0.000	4.803	0.094	0.000	158194.48	780.70	15897.52	0.00	3497.45	178370.15	0.00
Metals - Aluminium Foil	Metals	Aluminium - rolled	Internal finishes	Ceiling finishes	0.140	m^3	2700	1	0.1	416.14	kg	2	255.2	0	0	kg	9.180	0.029	0.921	0.000	10.332	0.203	0.000	3820.17	12.07	383.22	8599.54	84.31	12899.31	0.00
Metals - Aluminium Mullions	Metals	Aluminium - extruded	Superstructure	External walls	1074.930	m	2700	0.00115	0.1	3671.42	kg	0	255.2	0	0	kg	9.080	0.029	0.911	0.000	10.220	0.200	0.000	33336.51	106.47	3344.30	0.00	735.75	37523.03	0.00
Metals - Aluminium Section - Fascias	Metals	Aluminium - extruded	Superstructure	External walls	0.180	m^3	2700	1	0.1	533.94	kg	0	255.2	0	0	kg	9.080	0.029	0.911	0.000	10.220	0.200	0.000	4848.18	15.48	486.37	0.00	107.00	5457.03	0.00
Metals - Copper Pipe	Metals	Copper - Tube & Sheet	Services	Water installations	0.518	m^3	8600	1	0.05	4675.80	kg	2	255.2	0	0	kg	2.710	0.029	0.274	0.000	3.073	0.060	0.000	12671.42	135.60	1280.70	28738.95	281.75	43108.42	0.00
Miscellaneous - Lledo Rooflight	Miscellaneous	Rooflight EPD	Superstructure	Roof	72.000	ea	20	1	0	72.00	ea	1	185	0	0	ea	78.624	2.880	68.112	221.069	0.000	61.661	-50.688	5660.93	4147.20	4904.06	15916.95	4439.58	35068.72	-3649.54
Miscellaneous - Refridge Cabinet 1250	Miscellaneous	Refridge Cabinet 1250	Fittings, furnishings and equipment	Fittings, furnishings and equipment	200.000	ea	200	1	0	200.00	ea	2	185	0	0	ea	390.000	0.021	39.002	0.000	437.604	8.580	0.000	78000.00	840.94	7800.42	175041.44	1716.09	263398.88	0.00
Miscellaneous - Refridge Cabinet 1800	Miscellaneous	Refridge Cabinet 1800	Fittings, furnishings and equipment	Fittings, furnishings and equipment	10.000	ea	300	1	0	10.00	ea	2	185	0	0	ea	580.000	0.021	58.002	0.000	650.784	12.760	0.000	5800.00	63.07	580.02	13015.67	127.60	19586.37	0.00
Miscellaneous - Refridge Cabinet 2400	Miscellaneous	Refridge Cabinet 2400	Fittings, furnishings and equipment	Fittings, furnishings and equipment	2.000	ea	400	1	0	2.00	ea	2	185	0	0	ea	770.000	0.021	77.002	0.000	863.964	16.940	0.000	1540.00	16.82	154.00	3455.85	33.88	5200.56	0.00
Miscellaneous - Refridge Cabinet 2600	Miscellaneous	Refridge Cabinet 2600	Fittings, furnishings and equipment	Fittings, furnishings and equipment	5.000	ea	430	1	0	5.00	ea	2	185	0	0	ea	820.000	0.021	82.002	0.000	920.064	18.040	0.000	4100.00	45.20	410.01	9200.64	90.20	13846.05	0.00
Miscellaneous - Refridge Cabinet 800	Miscellaneous	Refridge Cabinet 0800	Fittings, furnishings and equipment	Fittings, furnishings and equipment	53.000	ea	130	1	0	53.00	ea	2	185	0	0	ea	250.000	0.021	25.002	0.000	280.524	5.500	0.000	13250.00	144.85	1325.11	29735.50	291.52	44746.99	0.00
Miscellaneous - Rockspan	Miscellaneous	Rockspan - 175mm (kg/m^2)	Superstructure	External walls	2109.940	m^2	27.14	1	0	2109.94	m^2	0	185	0	0	m^2	51.610	0.021	5.163	0.000	57.930	1.136	-14.630	108894.00	1203.88	10893.84	0.00	2396.64	123388.35	-30868.42
Mortar - for Blocks	Mortar	Mortar (1:1:6 Cement:Lime:Sand mix)	Superstructure	Internal walls and partitions	1.175	m^3	1600	1	0.2	2256.61	kg	0	136.4	0	0	kg	0.174	0.016	0.019	0.000	0.213	0.004	0.000	392.65	34.98	42.76	0.00	9.41	479.80	0.00
Mortar - Screed	Mortar	Mortar (1:4)	Internal finishes	Floor finishes	15.952	m^3	1900	1	0.2	36371.59	kg	0	136.4	0	0	kg	0.182	0.016	0.020	0.000	0.222	0.004	0.000	6619.63	563.78	718.34	0.00	158.03	8059.78	0.00
Plaster - Plasterboard	Plaster	Plasterboard	Superstructure	Internal walls and partitions	171.437	m^3	950	1	0.05	171008.20	kg	0	136.4	0	0	kg	0.390	0.016	0.041	0.000	0.455	0.009	0.000	66693.20	2650.71	6934.39	0.00	1525.57	77803.87	0.00
Plastics - HDPE Pipework	Plastics	Plastics - HDPE Pipe	Services	Water installations	0.122	m^3	970	1	0.05	124.06	kg	2	185	0	0	kg	2.520	0.021	0.254	0.000	2.851	0.056	0.000	312.64	2.61	31.52	707.41	6.94	1061.11	0.00
Plastics - PVC - Ceiling	Plastics	Plastics - PVC General	Internal finishes	Ceiling finishes	0.140	m^3	1330	1	0.03	191.94	kg	2	185	0	0	kg	3.100	0.021	0.312	0.000	3.502	0.069	0.000	595.02	4.04	59.91	1344.29	13.18	2016.43	0.00
Plastics - PVC - Roof	Plastics	Plastics - PVC General	Superstructure	Roof	1.975	m^3	1330	1	0.03	2705.79	kg	0	185	0	0	kg	3.100	0.021	0.312	0.000	3.502	0.069	0.000	8387.94	56.88	844.48	0.00	185.79	9475.09	0.00
Plastics - Vinyl Flooring	Plastics	Vinyl flooring	Internal finishes	Floor finishes	1.416	m^3	1300	1	0.05	1932.39	kg	2	185	0	0	kg	3.190	0.021	0.321	0.000	3.603	0.071	0.000	6164.31	40.63	620.49	13923.88	136.51	20885.83	0.00
Renewables - PV Panel	Renewables	PV Panel - Generic	Services	Services equipment	1200.000	m^2	12	1	0	1200.00	m^2	0	185	0	0	m^2	242.000	0.021	24.202	0.000	271.548	5.324	0.000	290400.00	302.74	29042.52	0.00	6389.36	326134.61	0.00
Steel - Carbon steel pipe	Steel	Steel - Pipe	Services	Space heating and air conditioning	0.067	m^3	7850	1	0.05	550.10	kg	2	255.2	0	0	kg	1.450	0.029	0.148	0.000	1.659	0.033	0.000	797.65	15.95	81.36	1825.72	17.90	2738.58	0.00
Steel - Gondola Bay 1000x470 High	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.052	m^3	7850	1	0.22	501.83	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	2070.07	14.55	208.46	4677.89	45.86	7016.84	-699.56
Steel - Gondola Bay 1250x370 High	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.742	m^3	7850	1	0.22	7106.13	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	29312.80	206.08	2951.89	66240.38	649.42	99360.57	-9905.95
Steel - Gondola Bay 1250x470 High	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.880	m^3	7850	1	0.22	8427.76	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	34764.51	244.41	3500.89	78560.02	770.20	117840.03	-11748.30
Steel - Gondola Bay 1250x470 Med	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.792	m^3	7850	1	0.22	7584.98	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	31288.06	219.97	3150.80	70704.02	693.18	106056.03	-10573.47
Steel - Gondola Bay 1250x570 High	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	9.131	m^3	7850	1	0.22	87451.42	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	360737.10	2536.17	36327.33	815185.22	7992.01	1222777.83	-121907.28
Steel - Gondola Bay 1250x570 Low	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.460	m^3	7850	1	0.22	4405.42	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	18172.36	127.76	1830.01	41065.47	402.60	61598.20	-6141.16
Steel - Gondola Bay 1250x570 Med	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.555	m^3	7850	1	0.22	5313.32	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	21917.44	154.09	2207.15	49528.52	485.57	74292.79	-7406.77
Steel - Gondola Bay 1250x670 High	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	4.356	m^3	7850	1	0.22	41717.41	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	172084.32	1209.84	17329.42	388872.11	3812.47	583308.17	-58154.07
Steel - Gondola Bay 1250x770 High	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	10.416	m^3	7850	1	0.22	99754.03	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	411485.38	2892.96	41437.83	929865.00	9116.32	1394797.50	-139057.12
Steel - Gondola Bay 625x470 High	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.061	m^3	7850	1	0.22	583.24	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	2405.86	16.91	242.28	5436.71	53.30	8155.07	-813.04
Steel - Gondola Bay 625x470 Med	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.029	m^3	7850	1	0.22	275.82	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	1137.75	8.00	114.57	2571.06	25.21	3856.58	-384.49
Steel - Gondola Bay 625x570 High	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.097	m^3	7850	1	0.22	928.97	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	3832.00	26.94	385.89	8659.46	84.90	12989.19	-1294.98
Steel - Gondola Bay 625x670 High	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.022	m^3	7850	1	0.22	210.69	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	869.11	6.11	87.52	1964.00	19.25	2946.00	-293.71
Steel - Partition Studs	Steel	Steel - Light steel framing	Superstructure	Internal walls and partitions	3.663	m^3	7850	1	0.1	31632.24	kg	0	255.2	0	0	kg	2.538	0.024	0.256	0.000	2.879	0.060	-1.450	80292.11	759.17	8105.13	0.00	1897.93	91054.34	-45866.74
Steel - Profile Deck	Steel	Steel - Decking - IFPS EPD 35mm	Superstructure	Roof	731.899	m^2	6.9	1	0.1	805.09	m^2	0	255.2	0	0	m^2	16.500	0.029	1.653	0.000	18.192	0.010	-9.620	13283.96	161.10	1330.73	0.00	8.05	14783.85	-7744.95
Steel - Profile Plant Deck	Steel	Steel - Decking - IFPS EPD 35mm	Superstructure	Roof	638.119	m^2	6.9	1	0.1	701.93	m^2	0	255.2	0	0	m^2	16.500	0.029	1.653	0.000	18.192	0.010	-9.620	11581.86	140.46	1160.22	0.00	7.02	12889.56	-6752.58
Steel - Section	Steel	Steel - Structural section incl fabrication	Superstructure	Frame	35.451	m^3	7850	1	0.1	306122.44	kg	0	255.2	0	0	kg	2.006	0.013	0.202	0.000	2.281	0.060	-0.959	614081.62	3979.59	61806.12	0.00	18367.35	698234.68	-293571.42
Steel - Light section	Steel	Steel - Light steel framing	Superstructure	Frame	5.530	m^3	7850	1	0.1	47747.98	kg	0	255.2	0	0	kg	2.538	0.024	0.256	0.000	2.879	0.060	-1.450	121198.70	1145.95	12234.47	0.00	2864.88	137444.00	-69234.57
Steel - Sheet - Ceiling Tiles	Steel	Steel - Coil (Sheet) - Darby	Internal finishes	Ceiling finishes	0.640	m^3	7850	1	0.22	6133.60	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	25301.11	177.88	2547.90	57174.85	560.54	85762.28	-8550.24
Steel - sheet - coldstore	Steel	Steel - Coil (Sheet) - Darby	Fittings, furnishings and equipment	Fittings, furnishings and equipment	2.409	m^3	7850	1	0.22	23070.31	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	95165.02	669.06	9583.41	215051.69	2108.35	322577.53	-32160.01
Steel - Sheet - Ductwork	Steel	Steel - Coil (Sheet) - Darby	Services	Ventilation	2.288	m^3	7850	1	0.22	21909.85	kg	2	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	90378.15	635.41	9101.36	204234.41	2002.30	306351.62	-30542.34
Steel - Sheet - Roof	Steel	Steel - Coil (Sheet) - Darby	Superstructure	Roof	7.406	m^3	7850	1	0.22	70927.26	kg	0	255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	292574.96	2056.96	29463.19	0.00	6481.90	330577.01	-98872.60
Steel - Wire	Steel	Steel - Wire - Virgin	Fittings, furnishings and equipment	Fittings, furnishings and equipment	0.088	m^3	7850	1	0.06	728.36	kg	2	255.2	0	0	kg	3.020	0.029	0.305	0.000	3.421	0.067	0.000	2199.65	21.12	222.08	4983.42	48.86	7475.13	0.00
Terrazzo - Terrazzo Tiling	Terrazzo	Terrazzo Tiles (CO2)	Internal finishes	Floor finishes	154.163	m^3	2100	1	0.05	339930.41	kg	1	136.4	0	0	kg	0.118	0.016	0.013	0.000	0.150	0.003	0.000	40111.79	5269.09	4538.09	50917.35	998.38	101834.69	0.00
																							Totals	**4328667.88**	**100018.17**	**441658.91**	**3310503.87**	**156069.85**	**8336918.69**	**-1199361.39**

Notes

- Resource = term used in Navisworks Quantity Take-Off to describe the materials that make up an element in the model such as a wall (see section 4.3.2)
- Resource Category = material categories that are common to both the quantity data and the carbon factors. This is what allows the selection of carbon factors to be semi-automated
- User Material Selection = materials selected by the user from a list of options determined by the resource category - this is what determines the carbon factors (see Appendix C for the full table of carbon factors)
- NRM = New Rules of Measurement (RICS, 2012b) L1 = Level 1 NRM categories L2 = Level 2 NRM categories
- ModelQuant = quantity data from Navisworks MQU = Model Quantity Units
- CalcQuant = material quantity value used to estimate embodied carbon. CQU = Calculated Quantity Units
- Calculation of CalcQuant values is based on the conversions listed in Table 4-8 on page 86. The conversion used depends on the MQU and CFU fields
- CFU = Functional unit of the carbon factors. Only the base unit (denominator) is shown, ie for $kgCO_2e/kg$ only kg appears. Other base units are m^3 or m^2 and in some cases m or ea (= each or per item)
- A1-3 CF etc. are the carbon factors for the life cycle stages based on the modularity principle of EN 15804 (British Standards Institution, 2014a)

Appendix E: Case Study 4-2 – Sainsbury's Leicester North – Quantity and Carbon Factor Data

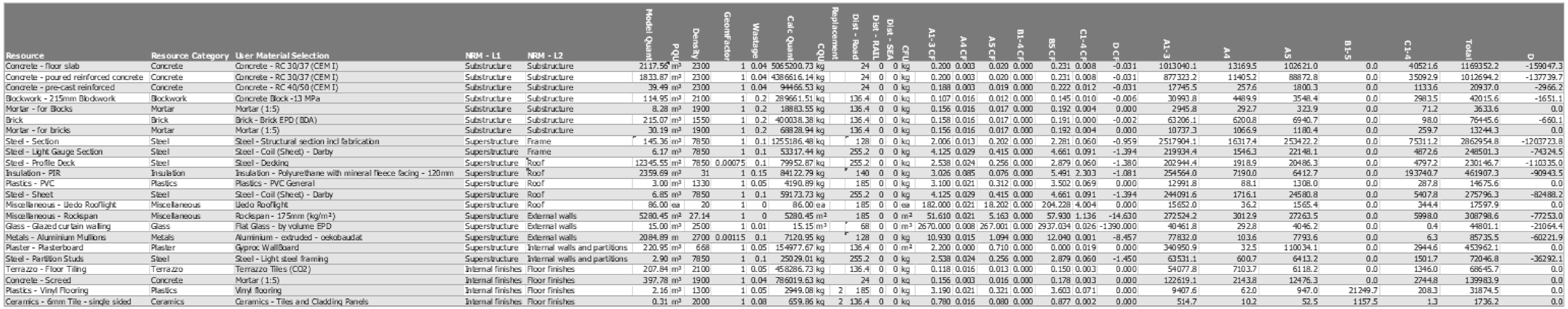


Resource	Resource Category	User Material Selection	NRM - L1	NRM - L2	Model Quant	MQU	Density	GeomFacto	Wastage	Calc Quant	CQU	Replacement	Dist - Road	Dist - RAIL	Dist - SEA	CFU	A1-3 CF	A4 CF	A5 CF	B1-4 CF	B5 CF	C1-4 CF	D CF	A1-3	A4	A5	B1-5	C1-4	Total	D
Concrete - floor slab	Concrete	Concrete - RC 32/40 (15% PFA)	Substructure	Substructure	2875.00	m^3	2300	1	0.04	6877000.00	kg		24	0	0	kg	0.152	0.003	0.015	0.000	0.182	0.012	-0.031	1045304.00	20358.67	106566.27	0.00	82524.00	1254752.94	-215937.80
Concrete - poured reinforced concrete	Concrete	Concrete - RC 32/40 (15% PFA)	Substructure	Substructure	1353.84	m^3	2300	1	0.04	3238395.62	kg		24	0	0	kg	0.152	0.003	0.015	0.000	0.182	0.012	-0.031	492236.13	9586.95	50182.31	0.00	38860.75	590866.14	-101685.62
Steel - Section	Steel	Steel - Structural section incl fabrication	Superstructure	Frame	59.76	m^3	7800	1	0.1	512781.12	kg		255.2	0	0	kg	2.006	0.013	0.202	0.000	2.281	0.060	-0.959	1028638.92	6666.15	103530.51	0.00	30766.87	1169602.45	-491757.09
Timber - Glulam	Timber	Timber - GlueLam	Superstructure	Frame	568.78	m^3	508	1	0.1	625.66	m^3		2800	0	100	m^3	-645.730	0.347	64.608	0.000	238.503	819.279	-372.400	-404009.23	110192.39	40422.61	0.00	512592.32	259198.10	-232996.82
Timber - SIPS Facing OSB 15mm	Timber	Timber - OSB sustainably sourced	Superstructure	Roof	168.68	m^3	600	1	0.1	185.55	m^3		271	0	0	m^3	-760.000	19.112	77.911	0.000	377.023	1040.000	-649.000	-141018.86	3546.21	14456.51	0.00	192973.18	69957.03	-120422.68
Timber - Birch Ply	Timber	Timber - Plywood	Superstructure	Roof	67.49	m^3	700	1	0.1	74.24	m^3		271	0	0	m^3	-824.000	92.500	91.650	0.000	610.150	1250.000	-577.000	-61172.98	6867.11	6804.01	0.00	92798.81	45296.96	-42835.93
Plastics - PVC	Plastics	Plastics - PVC General	Superstructure	Roof	15.39	m^3	1330	1	0.05	21490.25	kg		185	0	0	kg	3.100	0.023	0.312	0.000	3.504	0.069	0.000	66619.77	490.40	6711.02	0.00	1476.42	75297.62	0.00
Insulation - Mineral Wool	Insulation	Insulation - Mineral wool	Superstructure	Roof	1747.61	m^3	35	1	0.15	70341.33	kg		185	0	0	kg	1.280	0.023	0.130	0.000	1.462	0.029	0.000	90036.90	1605.17	9164.21	0.00	2016.13	102822.40	0.00
Timber - softwood battens	Timber	Timber - Sawn Softwood	Superstructure	Roof	37.16	m^3	485	1	0.1	40.88	m^3		271	0	0	m^3	-679.000	22.500	70.150	0.000	211.650	798.000	-366.000	-27757.50	919.80	2867.73	0.00	32622.22	8652.25	-14962.07
Timber - I-Beams	Timber	Timber - I-Beam	Superstructure	Roof	138.72	m^3	406	1	0.1	152.59	m^3		271	0	0	m^3	-418.707	12.576	43.128	0.000	312.797	675.800	-493.350	-63891.83	1919.01	6581.08	0.00	103122.44	47730.69	-75281.82
Paint - double coat	Paint	Paint - Double Coat (per m^2)	Superstructure	Roof	10259.09	m^2	2100	1	0	10259.09	m^2		185	0	0	m^2	0.064	0.023	0.009	0.000	0.097	0.002	0.000	656.21	234.11	89.03	0.00	19.59	998.94	0.00
Miscellaneous - Lledo Rooflight	Miscellaneous	Lledo Rooflight	Superstructure	Roof	122.00	ea	20	1	0	122.00	ea		185	0	0	ea	182.000	0.023	18.202	0.000	204.230	4.005	0.000	22204.00	2.78	2220.68	0.00	488.55	24916.01	0.00
Miscellaneous - Rockspan	Miscellaneous	Rockspan - 175mm (kg/m^2)	Superstructure	External walls	2716.31	m^2	27.14	1	0	2716.31	m^2		185	0	0	m^2	51.610	0.023	5.163	0.000	57.932	1.136	0.000	140189.02	1682.29	14025.10	0.00	3085.52	158981.93	0.00
Glass - Glazed curtain walling	Glass	Flat Glass - by volume EPD	Superstructure	External walls	644.03	m^2	2500	0.012	0.01	7.81	kg		136.4	0	0	m^3	2670.000	0.017	267.002	0.000	2995.759	58.740	-1390.000	20841.16	0.13	2084.13	0.00	458.51	23383.92	-10849.89
Metals - Aluminium Mullions	Metals	Aluminium - extruded	Superstructure	External walls	1429.61	m	2700	0.00115	0.1	4882.84	kg		255.2	0	0	kg	9.080	0.031	0.911	0.000	10.223	0.200	0.000	44336.20	153.71	4448.99	0.00	978.78	49917.68	0.00
Plaster - Plasterboard	Plaster	Gyproc WallBoard	Superstructure	Internal walls and partitions	172.56	m^3	668	1	0.05	121034.94	kg		136.4	0	0	m^2	2.200	0.000	0.710	0.000	0.000	0.000	0.000	266276.87	25.42	85934.81	0.00	6.17	352243.26	0.00
Steel - Partition Studs	Steel	Steel - Light steel framing	Superstructure	Internal walls and partitions	2.42	m^3	7800	1	0.1	20728.14	kg		255.2	0	0	kg	2.538	0.024	0.256	0.000	2.879	0.060	-1.450	52614.24	497.48	5311.17	0.00	1243.69	59666.57	-30055.80
Concrete - Terrazzo Tiling	Terrazzo	Terrazzo Tiles (CO2)	Internal finishes	Floor finishes	521.36	m^3	2100	1	0.05	1149597.96	kg		136.4	0	0	kg	0.118	0.017	0.013	0.000	0.151	0.003	0.000	135652.56	19341.92	15499.45	0.00	3409.88	173903.80	0.00
Concrete - Screed	Mortar	Mortar (1:5)	Internal finishes	Floor finishes	521.36	m^3	1900	1	0.2	1188699.94	kg		136.4	0	0	kg	0.156	0.017	0.017	0.000	0.194	0.004	0.000	185437.19	19999.81	20543.70	0.00	4519.61	230500.31	0.00
Plastics - Vinyl Flooring	Plastics	Vinyl flooring	Internal finishes	Floor finishes	1.62	m^3	1300	1	0.05	2217.41	kg	2	185	0	0	kg	3.190	0.023	0.321	0.000	3.605	0.071	0.000	7073.54	50.60	712.41	15986.58	156.73	23979.87	0.00
Steel - Galvanized steel ductwork	Steel	Steel - Coil (Sheet), Galvanised	Services	Space heating and air conditioning	0.63	m^3	7800	1	0.1	5447.29	kg		255.2	0	0	kg	1.540	0.031	0.157	0.000	1.763	0.035	0.000	8388.82	171.47	856.03	0.00	188.33	9604.65	0.00
																							Totals	**2908655.139**	**204311.5771**	**499011.7518**	**15986.58171**	**1104308.479**	**4732273.529**	**-1336785.534**

Notes

- Resource = term used in Navisworks Quantity Take-Off to describe the materials that make up an element in the model such as a wall (see section 4.3.2)
- Resource Category = material categories that are common to both the quantity data and the carbon factors. This is what allows the selection of carbon factors to be semi-automated
- User Material Selection = materials selected by the user from a list of options determined by the resource category - this is what determines the carbon factors (see Appendix C for the full table of carbon factors)
- NRM = New Rules of Measurement (RICS, 2012b) L1 = Level 1 NRM categories L2 = Level 2 NRM categories
- ModelQuant = quantity data from Navisworks MQU = Model Quantity Units
- CalcQuant = material quantity value used to estimate embodied carbon. CQU = Calculated Quantity Units
- Calculation of CalcQuant values is based on the conversions listed in Table 4-8 on page 86. The conversion used depends on the MQU and CFU fields
- CFU = Functional unit of the carbon factors. Only the base unit (denominator) is shown, ie for kgCO2e/kg only kg appears. Other base units are m^3 or m^2 and in some cases m or ea (= each or per item)
- A1-3 CF etc. are the carbon factors for the life cycle stages based on the modularity principle of EN 15804 (British Standards Institution, 2014a)

Appendix F: Case Study 4-3 – Sainsbury's Thanet – Quantity and Carbon Factor Data



Resource	Resource Category	User Material Selection	NRM - L1	NRM - L2	Model Quant	PQU	Density	GeomFactor	Wastage	Calc Quant	CQU	Replacement	Dist - Road	Dist - RAIL	Dist - SEA	CFU	A1-3 CF	A4 CF	A5 CF	B1-4 CF	B5 CF	C1-4 CF	D CF	A1-3	A4	A5	B1-5	C1-4	Total	D
Concrete - floor slab	Concrete	Concrete - RC 30/37 (CEM I)	Substructure	Substructure	2117.56	m³	2300	1	0.04	5065200.73	kg		24	0	0	kg	0.200	0.003	0.020	0.000	0.231	0.008	-0.031	1013040.1	13169.5	102621.0	0.0	40521.6	1169352.2	-159047.3
Concrete - poured reinforced concrete	Concrete	Concrete - RC 30/37 (CEM I)	Substructure	Substructure	1833.87	m³	2300	1	0.04	4386616.14	kg		24	0	0	kg	0.200	0.003	0.020	0.000	0.231	0.008	-0.031	877323.2	11405.2	88872.8	0.0	35092.9	1012694.2	-137739.7
Concrete - pre-cast reinforced	Concrete	Concrete - RC 40/50 (CEM I)	Substructure	Substructure	39.49	m³	2300	1	0.04	94466.53	kg		24	0	0	kg	0.188	0.003	0.019	0.000	0.222	0.012	-0.031	17745.5	257.6	1800.3	0.0	1133.6	20937.0	-2966.2
Blockwork - 215mm Blockwork	Blockwork	Concrete Block -13 MPa	Substructure	Substructure	114.95	m³	2100	1	0.2	289661.51	kg		136.4	0	0	kg	0.107	0.016	0.012	0.000	0.145	0.010	-0.006	30993.8	4489.9	3548.4	0.0	2983.5	42015.6	-1651.1
Mortar - for Blocks	Mortar	Mortar (1:5)	Substructure	Substructure	8.28	m³	1900	1	0.2	18883.55	kg		136.4	0	0	kg	0.156	0.016	0.017	0.000	0.192	0.004	0.000	2945.8	292.7	323.9	0.0	71.2	3633.6	0.0
Brick	Brick	Brick - Brick EPD (BDA)	Substructure	Substructure	215.07	m³	1550	1	0.2	400038.38	kg		136.4	0	0	kg	0.158	0.016	0.017	0.000	0.191	0.000	-0.002	63206.1	6200.8	6940.7	0.0	98.0	76445.6	-660.1
Mortar - for bricks	Mortar	Mortar (1:5)	Substructure	Substructure	30.19	m³	1900	1	0.2	68828.94	kg		136.4	0	0	kg	0.156	0.016	0.017	0.000	0.192	0.004	0.000	10737.3	1066.9	1180.4	0.0	259.7	13244.3	0.0
Steel - Section	Steel	Steel - Structural section incl fabrication	Superstructure	Frame	145.36	m³	7850	1	0.1	1255186.48	kg		128	0	0	kg	2.006	0.013	0.202	0.000	2.281	0.060	-0.959	2517904.1	16317.4	253422.2	0.0	75311.2	2862954.8	-1203723.8
Steel - Light Gauge Section	Steel	Steel - Coil (Sheet) - Darby	Superstructure	Frame	6.17	m³	7850	1	0.1	53317.44	kg		255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	219934.4	1546.3	22148.1	0.0	4872.6	248501.3	-74324.5
Steel - Profile Deck	Steel	Steel - Decking	Superstructure	Roof	12345.55	m²	7850	0.00075	0.1	79952.87	kg		255.2	0	0	kg	2.538	0.024	0.256	0.000	2.879	0.060	-1.380	202944.4	1918.9	20486.3	0.0	4797.2	230146.7	-110335.0
Insulation - PIR	Insulation	Insulation - Polyurethane with mineral fleece facing - 120mm	Superstructure	Roof	2359.69	m³	31	1	0.15	84122.79	kg		140	0	0	kg	3.026	0.085	0.076	0.000	5.491	2.303	-1.081	254564.0	7190.0	6412.7	0.0	193740.7	461907.3	-90943.5
Plastics - PVC	Plastics	Plastics - PVC General	Superstructure	Roof	3.00	m³	1330	1	0.05	4190.89	kg		185	0	0	kg	3.100	0.021	0.312	0.000	3.502	0.069	0.000	12991.8	88.1	1308.0	0.0	287.8	14675.6	0.0
Steel - Sheet	Steel	Steel - Coil (Sheet) - Darby	Superstructure	Roof	6.85	m³	7850	1	0.1	59173.73	kg		255.2	0	0	kg	4.125	0.029	0.415	0.000	4.661	0.091	-1.394	244091.6	1716.1	24580.8	0.0	5407.8	275796.3	-82488.2
Miscellaneous - Ledo Rooflight	Miscellaneous	Ledo Rooflight	Superstructure	Roof	86.00	ea	20	1	0	86.00	ea		185	0	0	ea	182.000	0.021	18.202	0.000	204.228	4.004	0.000	15652.0	36.2	1565.4	0.0	344.4	17597.9	0.0
Miscellaneous - Rockspan	Miscellaneous	Rockspan - 175mm (kg/m²)	Superstructure	External walls	5280.45	m²	27.14	1	0	5280.45	m²		185	0	0	m²	51.610	0.021	5.163	0.000	57.930	1.136	-14.630	272524.2	3012.9	27263.5	0.0	5998.0	308798.6	-77253.0
Glass - Glazed curtain walling	Glass	Flat Glass - by volume EPD	Superstructure	External walls	15.00	m³	2500	1	0.01	15.15	m³		68	0	0	m³	2670.000	0.008	267.001	0.000	2937.034	0.026	-1390.000	40461.8	292.8	4046.2	0.0	0.4	44801.1	-21064.4
Metals - Aluminium Mullions	Metals	Aluminium - extruded - oekobaudat	Superstructure	External walls	2084.89	m	2700	0.00115	0.1	7120.95	kg		128	0	0	kg	10.930	0.015	1.094	0.000	12.040	0.001	-8.457	77832.0	103.6	7793.6	0.0	6.3	85735.5	-60221.9
Plaster - Plasterboard	Plaster	Gyproc WallBoard	Superstructure	Internal walls and partitions	220.95	m³	668	1	0.05	154977.67	kg		136.4	0	0	m²	2.200	0.000	0.710	0.000	0.000	0.019	0.000	340950.9	32.5	110034.1	0.0	2944.6	453962.1	0.0
Steel - Partition Studs	Steel	Steel - Light steel framing	Superstructure	Internal walls and partitions	2.90	m³	7850	1	0.1	25029.01	kg		255.2	0	0	kg	2.538	0.024	0.256	0.000	2.879	0.060	-1.450	63531.1	600.7	6413.2	0.0	1501.7	72046.8	-36292.1
Terrazzo - Floor Tiling	Terrazzo	Terrazzo Tiles (CO2)	Internal finishes	Floor finishes	207.84	m³	2100	1	0.05	458286.73	kg		136.4	0	0	kg	0.118	0.016	0.013	0.000	0.150	0.003	0.000	54077.8	7103.7	6118.2	0.0	1346.0	68645.7	0.0
Concrete - Screed	Concrete	Mortar (1:5)	Internal finishes	Floor finishes	397.78	m³	1900	1	0.04	786019.63	kg		24	0	0	kg	0.156	0.003	0.016	0.000	0.178	0.003	0.000	122619.1	2143.8	12476.3	0.0	2744.8	139983.9	0.0
Plastics - Vinyl Flooring	Plastics	Vinyl flooring	Internal finishes	Floor finishes	2.16	m³	1300	1	0.05	2949.08	kg	2	185	0	0	kg	3.190	0.021	0.321	0.000	3.603	0.071	0.000	9407.6	62.0	947.0	21249.7	208.3	31874.5	0.0
Ceramics - 6mm Tile - single sided	Ceramics	Ceramics - Tiles and Cladding Panels	Internal finishes	Floor finishes	0.31	m³	2000	1	0.08	659.86	kg	2	136.4	0	0	kg	0.780	0.016	0.080	0.000	0.877	0.002	0.000	514.7	10.2	52.5	1157.5	1.3	1736.2	0.0

Notes

- Resource = term used in Navisworks Quantity Take-Off to describe the materials that make up an element in the model such as a wall (see section 4.3.2)
- Resource Category = material categories that are common to both the quantity data and the carbon factors. This is what allows the selection of carbon factors to be semi-automated
- User Material Selection = materials selected by the user from a list of options determined by the resource category - this is what determines the carbon factors (see Appendix C for the full table of carbon factors)
- NRM = New Rules of Measurement (RICS, 2012b) L1 = Level 1 NRM categories L2 = Level 2 NRM categories
- ModelQuant = quantity data from Navisworks MQU = Model Quantity Units
- CalcQuant = material quantity value used to estimate embodied carbon. CQU = Calculated Quantity Units
- Calculation of CalcQuant values is based on the conversions listed in Table 4-8 on page 86. The conversion used depends on the MQU and CFU fields
- CFU = Functional unit of the carbon factors. Only the base unit (denominator) is shown, ie for kgCO2e/kg only kg appears. Other base units are m³ or m² and in some cases m or ea (= each or per item)
- A1-3 CF etc. are the carbon factors for the life cycle stages based on the modularity principle of EN 15804 (British Standards Institution, 2014a)

Appendix G: Pre-Elicitation Briefing and Questionnaire

The following pages contain a sample of the briefing information and pre-elicitation questionnaire provided to each of the participants for the expert elicitations conducted in the course of this research.

Please enter your name here

This document provides some background to the workshop that you have been invited to attend on Tue 01 March.

Please could you enter your name above, read the briefing information and review the sample exercises.
Please then complete the questionnaire on pages 3 & 4 using the red fields provided and save and return the document by email to Stephen.richardson@sainsburys.co.uk
I would be very grateful if I could have your responses by 10am Monday 29 February.

All information provided will be treated as confidential in accordance with the consent form that you have been provided with previously and will only be viewed by the researcher and the research supervisors.

Purpose of the workshop
The workshop is one of two which form part of a method to assess uncertainty in the outcomes of embodied carbon assessments of buildings. The focus of this workshop will be on the carbon factors for different materials whilst the second workshop will focus on the generation of material quantities, though there is likely to be some overlap.
The objective of the workshop is to elicit the judgements of you, the expert participants, on the uncertainty in the inputs to the embodied carbon calculation. This is done in two exercises, firstly a quantitative assessment and then a qualitative assessment.
In the quantitative exercise, you will be asked to give your judgement on the range of values that particular inputs to the calculation could take by estimating upper and lower bounds.
In the qualitative exercise, you will be asked to score quality of different data sources using a pre-determined scoring matrix.

Desired outcomes
The outcomes from the quantitative assessment exercise will be used as part of a Monte-Carlo simulation. The Mote-Carlo simulation will estimate the overall uncertainty range for the case study building using probabilistic modelling.
The qualitative scoring outcomes will be used in conjunction with the Monte-Carlo results to assess the underlying quality of the data inputs and identify the most significant sources of uncertainty.

Please now review the sample exercises on page 2.

Sample Exercises

The following are examples of the exercises we will undertake during the workshop. These are part of the briefing information to encourage you to think through some of the issues that we will discuss and work on. You do not need to provide an answer or response to any of the questions on this page.

There will be a briefing at the workshop on how to complete the exercise. However, you may wish to note down any thoughts or questions that come up as you review the examples as it may be helpful to discuss these during the workshop.

Exercise 1 – Quantifying Uncertainty

The first exercise seeks to quantify the uncertainty in the different inputs to the embodied carbon calculation by asking you, the experts, to give your judgement of the possible range of values that each input could take – the upper and lower bounds. These can be expressed in different forms, for example as a range of absolute values or as percentage ranges.

As an example, please consider the **cradle-to-gate carbon factor of steel section** (or another building material that you are familiar with). Now consider what sources of uncertainty might affect that carbon factor. Examples include boundary conditions, production process, location of manufacture, steel grade and so forth.
Secondly, please consider how you would quantify the uncertainty range given the different sources of uncertainty.

In the exercise, you will be asked to give your judgement on the likely uncertainty ranges for a number of such carbon factors and data inputs to the embodied carbon calculation.

Exercise 2 – Assessment of Data Quality

The following is a sample of the data quality scoring matrix that we will use during the workshop. We will consider different types and sources of data used in embodied carbon calculations and score them against the four criteria shown in the column headings of the matrix.
Taking the example above of cradle-to-gate emissions for steel sections (or another material you are familiar with) please consider where and how that emission factor has been calculated and think through how you would score its quality using the matrix below.

Score	What is being measured / estimated	Reliability / Empirical basis	Method	Validation
4	Exact Measure	Data from direct measurements	Best available practice	Compared with independent measurements of same variable
3	Approximate measure	Data from measurements with some assumptions	Reliable method commonly accepted	Compared with independent measurements of closely related variable
2	Proxy with good correlation	Modelled/derived data	Acceptable method but limited consensus on reliability	Compared with measurements – not independent
1	Proxy with weak correlation	Qualified estimates/rule of thumb	Preliminary methods with unknown reliability	Weak/indirect validation
0	Proxy not clearly correlated	Crude speculation	No discernible rigor	No validation or validation not known

Please now complete the questionnaire on pages 3 & 4

Questionnaire for participants

Please answer the following questions which are designed to capture details of your experience and expertise.

1. Do you have any qualifications relevant to embodied carbon, carbon foot-printing or life cycle analysis? Please list all that apply.

Please enter details of any relevant qualifications here

2. How many years of professional work experience do you have in roles that deal/t with embodied carbon, carbon foot-printing or life cycle analysis of buildings or construction products?

Select number of year's experience

3. Have you conducted any embodied carbon assessments, carbon footprints or LCA of buildings or construction products?
   ☐Yes
   ☐No

   If yes, please estimate how many.
   Choose a number of studies undertaken

4. Do you have any areas of specialism, such as aspects of the building life cycle, particular construction materials or processes?

List any areas of specialism here

5. Please provide details of any publications that you have authored or contributed to which are relevant to embodied carbon, carbon foot-printing or LCA.

List any relevant publications here

6. Which of the following have you used as a source of embodied carbon data for construction materials?
   ☐Inventory of Carbon & Energy (Hammond & Jones / BSRIA, 2011)
   ☐Franklin & Andrews Black Book
   ☐Commercial database e.g. GaBi, EcoInvent etc.
   ☐Supplier EPDs (for the actual material or product used)
   ☐Supplier EPDs (for a different but comparable product than used)
   Others, please list
   List any other sources here

Questions continue on next page

7. Do you have data available to you that would help to quantify the uncertainty ranges of embodied carbon of construction materials?
   ☐Yes
   ☐No

   If yes, please provide a brief description.

Describe any data here

8. Would you be willing to make that data available for the purposes of this research project?
   ☐Yes
   ☐No

9. What do you consider to be the top three priorities for improving the quality of building-level embodied carbon calculations?
   1. Click here to enter text.
   2. Click here to enter text.
   3. Click here to enter text.

End of questions

Please save this document with your responses and return by email to Stephen.richardson@sainsburys.co.uk by 10am Monday 29 February.

Appendix H: Data Quality Scores

Table H-1: Data quality scores elicited from 10 experts for six commonly used sources of embodied carbon factor.

Source	**Literature**										**Industry**										**Govt.**									
Participant	A	B	C	D	E	F	G	H	I	J	A	B	C	D	E	F	G	H	I	J	A	B	C	D	E	F	G	H	I	J
What is measured	1	1	1	1	3	1	2	2	3	3	2	2	2	2	3	2	2	2	3	3	2	2	3	2	2	2	2	3	2	3
Reliability	1	2	1	2	3	1	3	3	1	2	3	3	2	4	3	3	3	3	2	3	2	2	3	2	2	2	1	2	1	
Method	0	2	2	1	2	2	2	1	3	2	1	2	2	3	3	2	1	3	2	2	3	2	3	2	3	2	2	2	4	2
Validation	1	1	1	1	3	1	0	4	2	1	2	4	2	2	3	2	0	0	1	1	2	2	2	2	3	1	0	1	1	1

Source	**Commercial LCA**										**PAS2050**										**EPD**									
Participant	A	B	C	D	E	F	G	H	I	J	A	B	C	D	E	F	G	H	I	J	A	B	C	D	E	F	G	H	I	J
What is measured	2	2	3	2	4	3	2	2	3	3	2	2	3	2	-	3	2	3	3		2	2	3	2	4	4	2	4	3	3
Reliability	3	1	3	3	4	3	3	2	2	3	2	2	3	4	-	3	2	2	3		3	3	4	4	4	4	3	3	3	3
Method	4	2	3	3	4	3	2	4	2	2	2	3	3	3	-	3	3	2	3		3	3	3	4	4	4	4	2	3	2
Validation	4	0	2	3	4	3	2	3	1	1	1	2	2	1	-	3	0	2	1		2	4	4	4	4	3	0	2	1	1

Appendix I: Carbon Factors for Different Types of Timber used in Uncertainty Assessments

Table I-1: Carbon factors derived for assessing scenario uncertainty of the embodied carbon of glulam timber

Scenario Number	Credit for Sequestration	End of Life Treatment	A1	A2-3	A1-3		A4		C1-4	D	
			kgCO2e/m3	kgCO2e/m3	kgCO2e/m3	Sources	kgCO2e/m3	Sources	kgCO2e/m3	kgCO2e/m3	Sources
Glulam - 1	Seq	LF1	-730.20	242.20	-488.00	1	37.20	3	90.60	-0.22	4
Glulam - 2	Seq	LF2	-730.20	242.20	-488.00		37.20		934.00	-79.10	5
Glulam - 3	Seq	I	-730.20	242.20	-488.00		37.20		846.00	0.00	5
Glulam - 4	Seq	IER	-730.20	242.20	-488.00		37.20		846.00	-593.00	5
Glulam - 5	Seq	RU	-730.20	242.20	-488.00		37.20		819.00	-8.41	5
Glulam - 6	No Seq	LF1	57.80	242.20	300.00	2	37.20		90.60	-0.22	4
Glulam - 7	No Seq	LF2	57.80	242.20	300.00		37.20		934.00	-79.10	5
Glulam - 8	No Seq	I	57.80	242.20	300.00		37.20		846.00	0.00	5
Glulam - 9	No Seq	IER	57.80	242.20	300.00		37.20		846.00	-593.00	5
Glulam - 10	No Seq	RU	57.80	242.20	300.00		37.20		31.00	-8.41	6

Notes:

Seq = Credit given for carbon sequestered in the growth cycle
No Seq = No credit for sequestered carbon
LF1 and LF 2= Landfill with low and high decay rate, respectively (see section 6.2.3.2)
I = Incineration without energy recovery
IER = Incineration with energy recovery
RU = Re-use

Sources:

1. Wood for Good Lifecycle Database – Glued Laminated Timber (Wood for Good, 2013a, p. 4)
2. See Table 6-12 on page 159 and discussion in section 6.2.3.1 for details of how the carbon factors for the no sequestration scenarios are derived.
3. Calculated based on 1400km by road from central Europe (plus return) and 100km by sea. Vehicle emissions from DEFRA Carbon Factors. (Department for Environment, Food and Rural Affairs, 2015)
4. Wood Solutions Australia (2015a, pp. 10 & 14) and includes estimate of transport for waste from Steel Construction Institute (n.d.)
5. Wood for Good (2013a, p. 5)
6. Calculated by subtracting the estimated sequestered or biogenic carbon (British Standards Institution, 2014b, p. 5 Equation 1) from the value for reuse in Wood for Good (2013a, p. 5)

Table I-2: Carbon factors derived for assessing scenario uncertainty of the embodied carbon of Oriented Strand Board (OSB)

Scenario Number	Credit for Sequestration	End of Life Treatment	A1	A2-3	A1-3		A4		C1-4	D	
			kgCO2e/m3	kgCO2e/m3	kgCO2e/m3	Sources	kgCO2e/m3	Sources	kgCO2e/m3	kgCO2e/m3	Sources
OSB - 1	Seq	LF1	-943.10	183.10	-760.00	1	19.11	3	103.80	-3.38	4
OSB - 2	Seq	LF2	-943.10	183.10	-760.00		19.11		1144.00	-37.80	5
OSB - 3	Seq	I	-943.10	183.10	-760.00		19.11		1040.00	0.00	5
OSB - 4	Seq	IER	-943.10	183.10	-760.00		19.11		1040.00	-649.00	5
OSB - 5	Seq	RU	-943.10	183.10	-760.00		19.11		1040.00	-20.90	5
OSB - 6	No Seq	LF1	57.80	183.10	240.90	2	19.11		103.80	-3.38	4
OSB - 7	No Seq	LF2	57.80	183.10	240.90		19.11		1144.80	-37.80	5
OSB - 8	No Seq	I	57.80	183.10	240.90		19.11		1040.00	0.00	5
OSB - 9	No Seq	IER	57.80	183.10	240.90		19.11		1040.00	-649.00	5
OSB - 10	No Seq	RU	57.80	183.10	240.90		19.11		39.10	-20.90	6

Notes:
Seq = Credit given for carbon sequestered in the growth cycle
No Seq = No credit for sequestered carbon
LF1 and LF 2= Landfill with low and high decay rate, respectively (see section 6.2.3.2)
I = Incineration without energy recovery
IER = Incineration with energy recovery
RU = Re-use

Sources:

1. SWISS KRONO OSB-Platten EPD (Institut Bauen und Umwelt e.V., 2015a)
2. See Table 6-12 on page 159 and discussion in section 6.2.3.1 for details of how the carbon factors for the no sequestration scenarios are derived.
3. Calculated based on average road transport distances for timber in the UK (Department for Transport, 2016). Vehicle emissions from DEFRA Carbon Factors. (Department for Environment, Food and Rural Affairs, 2015)
4. Wood Solutions Australia (Wood Solutions Australia, 2015b, pp. 14 & 18)
5. SWISS KRONO OSB-Platten EPD (Institut Bauen und Umwelt e.V., 2015a)
6. Calculated by subtracting the estimated sequestered or biogenic carbon (British Standards Institution, 2014b, p. 5 Equation 1) from the value for reuse in SWISS KRONO OSB-Platten EPD (Institut Bauen und Umwelt e.V., 2015a)

Table I-3: Carbon factors derived for assessing scenario uncertainty of the embodied carbon of Oriented Strand Board (OSB)

Scenario Number	Credit for Sequestration	End of Life Treatment	A1	A2-3	A1-3		A4		C1-4	D	
			kgCO2e/m3	kgCO2e/m3	kgCO2e/m3	Sources	kgCO2e/m3	Sources	kgCO2e/m3	kgCO2e/m3	Sources
Birch Ply - 1	Seq	LF1	-1090	266.00	-824.00	1	92.50	3	103.80	-3.38	4
Birch Ply - 2	Seq	LF2	-1090	266.00	-824.00		92.50		1170.00	-99.09	5
Birch Ply - 3	Seq	I	-1090	266.00	-824.00		92.50		1250.00	0.00	5
Birch Ply - 4	Seq	IER	-1090	266.00	-824.00		92.50		1250.00	-577.00	5
Birch Ply - 5	Seq	RU	-1090	266.00	-824.00		92.50		1250.00	-18.90	5
Birch Ply - 6	No Seq	LF1	57.80	266.00	323.80	2	92.50		103.80	-3.38	4
Birch Ply - 7	No Seq	LF2	57.80	266.00	323.80		92.50		1170.00	-99.09	5
Birch Ply - 8	No Seq	I	57.80	266.00	323.80		92.50		1250.00	0.00	5
Birch Ply - 9	No Seq	IER	57.80	266.00	323.80		92.50		1250.00	-577.00	5
Birch Ply - 10	No Seq	RU	57.80	266.00	323.80		92.50		1250.00	-18.90	6

Notes:
Seq = Credit given for carbon sequestered in the growth cycle
No Seq = No credit for sequestered carbon
LF1 and LF 2= Landfill with low and high decay rate, respectively (see section 6.2.3.2)
I = Incineration without energy recovery
IER = Incineration with energy recovery
RU = Re-use

Sources:

1. Rüter and Diederichs (2012, p. 192)
2. See Table 6-12 on page 159 and discussion in section 6.2.3.1 for details of how the carbon factors for the no sequestration scenarios are derived.
3. Calculated based on average road transport distances for timber in the UK (Department for Transport, 2016). Vehicle emissions from DEFRA Carbon Factors. (Department for Environment, Food and Rural Affairs, 2015)
4. Wood Solutions Australia (2015a, pp. 10 & 14)
5. Rüter and Diederichs (2012, p. 192)
6. Calculated by subtracting the estimated sequestered or biogenic carbon (British Standards Institution, 2014b, p. 5 Equation 1) from the value for reuse in Wood for Good (2013a, p. 5)

Table I-4: Carbon factors derived for assessing scenario uncertainty of the embodied carbon of Oriented Strand Board (OSB)

Scenario Number	Credit for Sequestration	End of Life Treatment	A1	A2-3	A1-3		A4		C1-4	D	
			kgCO2e/m3	kgCO2e/m3	kgCO2e/m3	Sources	kgCO2e/m3	Sources	kgCO2e/m3	kgCO2e/m3	Sources
Softwood - 1	Seq	LF1	-715.20	36.20	-679.00	1	22.50	3	61.20	-0.22	4
Softwood - 2	Seq	LF2	-715.20	36.20	-679.00		22.50		943.00	-79.90	5
Softwood - 3	Seq	I	-715.20	36.20	-679.00		22.50		798.00	0.00	5
Softwood - 4	Seq	IER	-715.20	36.20	-679.00		22.50		798.00	-366.00	5
Softwood - 5	Seq	RU	-715.20	36.20	-679.00		22.50		798.00	-14.40	5
Softwood - 6	No Seq	LF1	57.80	36.20	94.00	2	22.50		61.20	-0.22	4
Softwood - 7	No Seq	LF2	57.80	36.20	94.00		22.50		943.00	-79.90	5
Softwood - 8	No Seq	I	57.80	36.20	94.00		22.50		798.00	0.00	5
Softwood - 9	No Seq	IER	57.80	36.20	94.00		22.50		798.00	-366.00	5
Softwood - 10	No Seq	RU	57.80	36.20	94.00		22.50		798.00	-14.40	6

Notes:
Seq = Credit given for carbon sequestered in the growth cycle
No Seq = No credit for sequestered carbon
LF1 and LF 2= Landfill with low and high decay rate, respectively (see section 6.2.3.2)
I = Incineration without energy recovery
IER = Incineration with energy recovery
RU = Re-use

Sources:

1. Wood for Good Lifecycle Database – Kiln Dried Softwood (Wood for Good, 2013b, p. 5)
2. See Table 6-12 on page 159 and discussion in section 6.2.3.1 for details of how the carbon factors for the no sequestration scenarios are derived.
3. Calculated based on average road transport distances for timber in the UK (Department for Transport, 2016). Vehicle emissions from DEFRA Carbon Factors. (Department for Environment, Food and Rural Affairs, 2015)
4. Wood Solutions Australia (2015a, pp. 10 & 14)
5. Wood for Good (Wood for Good, 2013b, p. 5)
6. Calculated by subtracting the estimated sequestered or biogenic carbon (British Standards Institution, 2014b, p. 5 Equation 1) from the value for reuse in Wood for Good (Wood for Good, 2013b, p. 5)

Table I-5: Carbon factors derived for assessing scenario uncertainty of the embodied carbon of Oriented Strand Board (OSB)

Scenario Number	Credit for Sequestration	End of Life Treatment	A1	A2-3	A1-3		A4		C1-4	D	
			kgCO2e/m3	kgCO2e/m3	kgCO2e/m3	Sources	kgCO2e/m3	Sources	kgCO2e/m3	kgCO2e/m3	Sources
I-Beam - 1	Seq	LF1	-582.50	221.60	-418.71	1	12.58	3	97.60	-1.64	4
I-Beam - 2	Seq	LF2	-582.50	221.60	-418.71		12.58		1033.45	-60.96	5
I-Beam - 3	Seq	I	-582.50	221.60	-418.71		12.58		675.80	0.00	6
I-Beam - 4	Seq	IER	-582.50	221.60	-418.71		12.58		675.80	-493.35	6
I-Beam - 5	Seq	RU	-582.50	221.60	-418.71		12.58		675.80	-17.33	6
I-Beam - 6	No Seq	LF1	57.80	221.60	279.40	2	12.58		97.60	-0.22	4
I-Beam - 7	No Seq	LF2	57.80	221.60	279.40		12.58		1033.81	-60.96	5
I-Beam - 8	No Seq	I	57.80	221.60	279.40		12.58		675.80	0.00	6
I-Beam - 9	No Seq	IER	57.80	221.60	279.40		12.58		675.80	-366.00	6
I-Beam - 10	No Seq	RU	57.80	221.60	279.40		12.58		675.80	-14.40	7

Notes:

Seq = Credit given for carbon sequestered in the growth cycle
No Seq = No credit for sequestered carbon
LF1 and LF 2= Landfill with low and high decay rate, respectively (see section 6.2.3.2)
I = Incineration without energy recovery
IER = Incineration with energy recovery
RU = Re-use

Sources:

1. Masonite Timber I-Beam EPD (Norwegian EPD Foundation, 2015)
2. See Table 6-12 on page 159 and discussion in section 6.2.3.1 for details of how the carbon factors for the no sequestration scenarios are derived.
3. Calculated based on average road transport distances for timber in the UK (Department for Transport, 2016). Vehicle emissions from DEFRA Carbon Factors. (Department for Environment, Food and Rural Affairs, 2015)
4. Masonite Timber I-Beam EPD (Norwegian EPD Foundation, 2015) – the quantity of sequestered carbon retained under the low decay rate is estimated by applying the factor from and Wood Solutions Australia (2015a, pp. 10 & 14)
5. Estimated value based on data for softwood and OSB (see Table I-4 and Table I-2) (the main constituents of I-beams) and assuming a volume ratio of 55:45 (softwood to OSB)
6. Masonite Timber I-Beam EPD (Norwegian EPD Foundation, 2015)
7. Calculated by subtracting the estimated sequestered or biogenic carbon (British Standards Institution, 2014b, p. 5 Equation 1) from the value for reuse in Masonite Timber I-Beam EPD (Norwegian EPD Foundation, 2015)