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Embodied Carbon in Building Services Systems

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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

Robust estimation of the environmental impacts of commercial buildings during early building design can support the ability to choose a design with demonstrably lower carbon emissions than other alternatives. However, gaps currently exist in the methods, tools and supporting data required to estimate embodied carbon emissions, especially for building services systems. This thesis aims to help address those gaps by developing an embodied carbon estimation method able to inform choices of those systems during building design.

Estimation of embodied carbon of a proposed building services design requires knowledge of raw material types and quantities of all its components as well as the relevant carbon emission factors for each material applicable to the life cycle stage of the component being considered. The relative scarcity of available data on raw material types and quantities used in building services systems makes the estimate subject to considerable uncertainty. A method is therefore needed to generate the estimate using limited source data whilst quantifying this uncertainty. Previous research on embodied carbon estimation has mainly used deterministic methods, which can generate misleading conclusions when comparing products. This study investigates the applicability of first-order analytical uncertainty propagation (AUP) combined with a parametric approach to estimate embodied carbon of heating, ventilation and air conditioning (HVAC) components and systems, using a series of empirical case studies. The AUP approach is tested against Monte Carlo simulation to determine whether it can offer a computationally efficient alternative for supporting rapid decisions during early building design. The resulting method is outlined in a specification for a decision support tool.

The study also examines – and provides depth of understanding on - choice mechanisms used by designers to select systems of building services and explores the ways in which information on embodied carbon emissions might influence the choice. The readiness of designers to reduce embodied carbon is also informed by societal barriers and drivers associated with an environmental intervention not widely used by industry, in that it prioritises environmental impacts of building services systems that happen prior to their operational use in completed buildings. Decision-making is investigated via a qualitative study of mechanical services designers and wider social factors are investigated using a survey of construction practitioners. Theories of rational choice and bounded rationality are explored as a framework to explain decisions by practitioners and to inform possible decision support measures. The results of both studies are used to inform the design of the embodied carbon estimation method and the specification for the decision support tool.

The parametric estimation method is shown to support comparisons of embodied carbon of HVAC components and systems for which input parameters are uncertain and can be continuously improved by an iterative process as additional empirical data becomes available. Insights into decision making by practitioners highlight the scope of influence of mechanical services designers on decisions that may reduce embodied carbon as well as identifying interventions able to improve decision support in this area. Recommendations for further research include expansion of the estimation method to cover additional building service systems and estimation of operational carbon emissions.

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List of Publications

Conference papers

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Medas, M., Cheshire., D, Cripps, A., Connaughton, J. and Peters, M., 2015. Towards BIM-integrated, resource-efficient building services. In *Technologies for Sustainable Built Environments (TSBE) annual conference*. Reading, 7 July, 2015: University of Reading.

Medas, M., Cheshire., D, Cripps, A., Connaughton, J. and Peters, M., 2015. Towards BIM-integrated, resource-efficient building services. In *7th International Conference of Sustainable Development in Building and Environment (SUDBE).* Reading, 27-29 July 2015: University of Reading.

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Medas, M., Cheshire., D, Cripps, A., Connaughton, J. and Peters, M., 2016. Reducing uncertainty in predicting embodied energy of HVAC systems. In *ASHRAE summer conference*. St. Louis MO, 25-29 June 2016: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

Medas, M., Cheshire., D, Cripps, A., Connaughton, J. and Peters, M., 2016. Uncertainty, embodied carbon and HVAC systems. In *TSBE annual conference.*, University of Reading, 5 July 2016.

Abbreviations and acronyms used in this thesis

AEC	Architecture, engineering and construction
AHU	Air-handling unit
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
AUP	Analytical uncertainty propagation
BCO	British Council for Offices
BEA	Building environmental assessment
BEIS	Department for Business, Energy and Industrial Strategy
BIM	Building information modelling
BOM	Bill of materials
BREEAM	Building Research Establishment Environmental Assessment Method
BSE	Building services engineer
BSI	British Standards Institution
BSRIA	Building Services Research and Information Association
CCC	Committee on Climate Change
CIBSE	Chartered Institute of Building Services Engineers
CIG	Carbon intensity of grid electricity
CO_2e	Carbon dioxide equivalent
CPD	Continuing professional development
CTV	Contribution to variance
CV	Coefficient of variation
DECC	Department of Energy and Climate Change
DEFRA	Department for Environment, Food and Rural Affairs
DX	Direct expansion
DV	Displacement ventilation
EE	Embodied energy
EEA	European Environment Agency
EC	Embodied carbon
ECC	Embodied carbon coefficient
EPD	Environmental product declaration
EPSRC	Engineering and Physical Sciences Research Council
FATVAV	Fan-assisted variable air volume
FCU	Fan coil unit
FIA	Fuzzy interval analysis
GFA	Gross floor area
GIFA	Gross internal floor area
GHG	Greenhouse gas
GLA	Greater London Authority
GWP	Global Warming Potential
HVAC	Heating, ventilation and air-conditioning
ICE	Inventory of Carbon and Energy
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
kg	Kilogramme
kWh	Kilowatt hour

LEED	Leadership in Energy and Environmental Design
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LHCS	Latin hypercube simulation
LCI	Life cycle inventory
MCDM	Multi-criteria decision making
MCS	Monte Carlo simulation
MEP	Mechanical, electrical and public health
MMR	Mixed methods research
MSE	Mechanical building services engineer
Mt	Million tonnes
NIA	Net internal floor area
OC	Operational carbon (emissions)
OE	Operational energy (consumption)
PUR	Polyurethane
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
RO	Research objective
RQ	Research question
SD	Standard deviation
SEM	Standard error of the mean
SQB	Status quo bias
TCC	Total cooling capacity
TSBE	Technologies for Sustainable Built Environments
UA	Uncertainty analysis
UNEP	United Nations Environment Programme
UNFCC	United Nations Framework on Climate Change
VAV	Variable air volume
VBA	Visual Basic for Applications
VRF	Variable refrigerant flow
VRV	Variable refrigerant volume
VRM	Various raw materials
WRAP	Waste Resources and Action Plan

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1 Introduction

1.1 Background and motivation

The impetus for this study arises from the recognition that collectively buildings and construction are responsible for approximately 40% of global energy use, 30% of energy-related greenhouse gas (GHG) emissions and nearly 40% of waste (UNEP 2016). Most extant research on the measurement and reduction of these GHG emissions has to date focused on operational emissions arising from building use, as these were traditionally believed to represent the largest proportion of emissions across the life cycle of buildings (Ibn-Mohammed et al, 2013). In the UK, action to mitigate operational emissions is also driven by binding national commitments under the Kyoto Protocol, the European Energy Performance of Buildings Directive and the Climate Change Act and implemented via building regulations (United Nations Framework on Climate Change, 2018, European Parliament and Council of the European Union, 2010, Climate Change Act, 2008, HM Government, 2016). However, 'embodied' emissions from other stages of the life cycle of building elements from raw material extraction to final disposal now represent a 'significant and growing proportion' of emissions (Birgisdottir et al, 2017, p73), partly because successful regulation of operational emissions has lowered their relative share of emissions over the building life cycle.

Against this background, this study focuses on embodied carbon emissions, defined as those associated with the stages of raw material extraction, transport and manufacturing of building services systems prior to their operational use within UK office buildings. This phase of the life cycle of a building is known as the 'product stage' (British Standards Institute, 2011) when conducting an environmental life cycle assessment (LCA) of the building. The term 'carbon emissions' in this thesis refers to CO_2 equivalent used to measure Global Warming Potential (GWP_{100}) calculated over a 100-year period (IPCC, 2013).

While this study focuses on product stage embodied carbon, a broader definition of embodied carbon for buildings and building elements can include 'recurring' embodied impacts from maintenance, repair, replacement and refurbishment as well as the non-recurring impacts of building construction and final demolition (Ibn-Mohammed et al, 2013, UK Green Building Council, 2017). The reasons for the focus on product stage embodied emissions of building services systems are as follows. Firstly, the majority of research on embodied emissions of buildings has examined the simpler raw materials used in the building structure and envelope rather than the complex range of materials used in building services (Passer et al, 2012). Secondly, existing research suggests that building services are responsible for 5-15% of initial embodied carbon (EC) of modern office buildings (CIBSE, 2014a), a proportion that increases when the 'recurring' embodied carbon from replacing components every 15-20 years is added. Thirdly, the trend towards buildings with low or 'zero' operational carbon or energy means that embodied emissions of all building elements may become a greater proportion of total carbon emissions within the building life cycle (RICS, 2010, Basbagill et al, 2013, Birgisdottir et al, 2017). Measurement and reduction of embodied impacts are therefore almost certain to become increasingly relevant to meeting national and global emissions targets, both as a dedicated activity and within 'whole-life' assessments of operational and embodied impacts of buildings.

1.2 Research problem

The challenge that this thesis focuses on arises from two linked issues. The first concerns the estimation of embodied carbon in building services systems and the second concerns the means by which such estimation can address uncertainty. Uncertainty has been broadly defined as 'any departure from complete determinism' (Walker, 2003, p4.). In a building design context, uncertainty can mean the level of unexpected variation of parameters such as cost, energy use or GHG emissions against planned target values that are set in advance for a construction project. Managing uncertainty of these parameters is therefore an integral part of construction project management. This can be illustrated by the 'cone of uncertainty', a concept used in project management (McConnell, 2006), which is shown in Figure 1.1 by two plot lines representing maximum and minimum variations of selected design parameters at each stage of building design as defined by the RIBA Plan of Work (RIBA, 2013). A copy of the complete Plan of Work is included in Appendix 1 for reference.

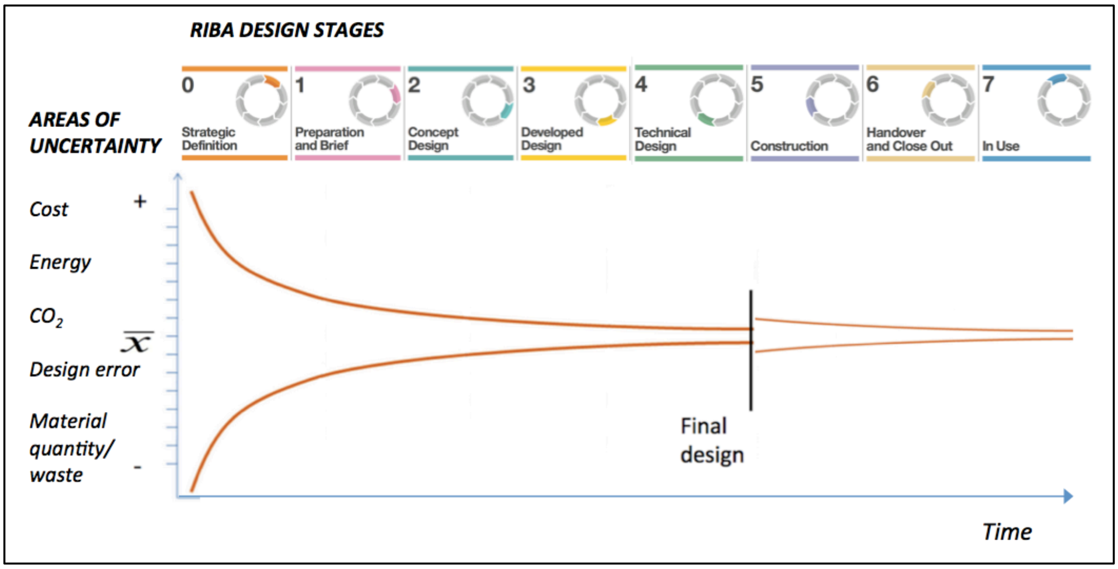

Figure 1-1: Uncertainty in building design, adapted from McConnell (2006)

In Figure 1.1, design parameter values, examples of which are shown on the vertical axis, become less uncertain as the design progresses through the stages situated in a chronological sequence along the horizontal axis from left to right. Parameter uncertainty never reaches zero because there is always residual uncertainty in the process of estimation or measurement, but it can become low enough for an estimate or measurement to be deemed acceptably accurate. While uncertainty about parameter values of the final design falls to its lowest value when the 'technical' design is completed at the end of RIBA stage 4, parameter values for the subsequent design stages are initially more uncertain because additional sources of uncertainty can arise. This is shown by the increased width of the cone of uncertainty to the right of the vertical line marked 'final design'. In projects where the design and construction teams represent separate commercial entities, these may include uncertainty about the extent to which product and material choices made during procurement will differ from those specified in the final design.

Despite the presence of uncertainty, some advance knowledge of parameter values is required in building design at or before the concept design stage. This enables design teams to compare and select alternative design options that meet target values for the parameter(s). Ideally, estimation of these values should be calibrated against data measured from completed buildings. This is currently feasible for operational energy consumption, operational carbon emissions and capital cost but far more challenging for embodied carbon. For example, the use of measured data on operational energy consumption as an input to the estimation model can help reduce the 'performance gap' between planned and actual energy use in buildings (CIBSE, 2013). This allows a proposed design of a system of building services to be associated with an estimated range of values of operational energy use and carbon emissions. However, whilst operational emissions can be measured in the present by investigating the carbon intensity of electricity generation associated with a unit of energy consumption, embodied emissions must be estimated retrospectively based on past emissions in the supply chain for finished products. To do so in turn requires knowing the proportions of individual raw materials contained in a finished product as well as the embodied emissions associated with each raw material. The greater the difficulty of estimating embodied carbon during building design, the greater will be the uncertainty shown by the vertical gap between the two plot lines in Figure 1.1, indicating a range of variation of estimated values that can be too large to guide meaningful choices of alternative materials with the lowest embodied carbon.

The estimation of embodied carbon in building services and the use of estimated values to inform design decisions faces three main challenges, relating to gaps in data metrics and tools, the absence of policy or market drivers and design choice. The first and the third of these challenges also involve uncertainty.

1.2.1 Data, metrics and tools

The first challenge concerns the relative scarcity of robust and accessible data, metrics and tools to support estimation. This is especially problematic for 'composite' components, which are components composed of multiple raw materials that are widely used within building services systems. Examples of composite components in mechanical services systems include chillers, boilers, terminal units and air handling units. For composite components, the individual material type, mass and product stage GHG emissions may either be unknown or too uncertain to support choice between products based on their embodied carbon intensity.

To compound the challenge, a particular selection of components, both composite and otherwise, will be contained in a given 'system' of building services, referred to in LCA standards as a 'integrated building technical system' (BSI, 2011, p23). Whilst the quantities of individual raw materials in a building structure can usually be estimated based on early design data about building size, spatial form and choice of main materials, the raw material quantities in a system of building services cannot. This is because they depend on knowledge of (a) the raw material content of composite components and (b) the unique choice of components associated with a particular technical system and its sub-systems. This would include the technical systems for mechanical, electrical or public health services. Gaps in knowledge about these two topics make embodied carbon estimation for building services systems particularly subject to uncertainty about input parameters values for raw material masses.

By contrast, estimation of embodied carbon for the raw materials used in building structures such as steel and concrete may be informed by designed or installed values for material mass, although as with composite components there will still be uncertainty about the carbon emission factors or coefficients within the supply chain of each raw material (Richardson, 2017). It follows that a methodology to estimate embodied carbon in building services systems, given current data gaps, must address parameter uncertainty primarily on raw material types and amounts but also on emissions factors.

1.2.2 Policy and market drivers

The second challenge is the relative absence of policy or market drivers in the UK that might encourage increased industry activity and improvements in embodied carbon estimation methods in a way similar to the role of building regulations in stimulating measurement of operational carbon by setting thermal efficiency standards for building fabric (Ibn-Mohammed et al, 2013). It is relevant therefore to explore both the barriers and the drivers in construction policy and markets that can stimulate or hinder practice on embodied carbon estimation. Without such an investigation it cannot be assumed that any improved estimation methods would be used by practitioners.

1.2.3 Design choice

The third challenge can be seen as another kind of uncertainty. It is, in a sense, uncertain how and why particular building services systems are, or should be, selected in practice by design teams for office buildings. Previous research on heating, ventilation and air conditioning (HVAC) systems has approached this as an optimisation problem (Shahrestani et al, 2012), although the present study argues that it also concerns the question of why and how designers might decide to use information about embodied carbon impacts to inform a design choice. This is relevant because it should not be assumed that the mere provision of data on possible environmental impacts would guarantee the use of that data by design practitioners. Moreover, the study of HVAC design choice is also needed to understand the extent to which generic types of building-wide HVAC systems can be seen as identifiable, alternative options defined by their technology and/or functions, rather than a spectrum of unique combinations of equipment. As will be shown later, classifying likely variations in raw materials between different types of HVAC systems can reduce some of the parameter uncertainty associated with estimating embodied carbon of an HVAC system during early building design. This in turn can make it easier to quantify other aspects of parameter uncertainty using uncertainty propagation.

1.3 Relevance to the construction industry

The practical limitations around embodied carbon estimation also represent further challenges. To achieve the aspirational goals of 'resource efficiency' and the 'circular economy', (EEA, 2016) would entail extending the definition of a 'zero carbon' building beyond the operational phase of building life to include embodied emissions. This in turn would require reliable data, metrics and tools to measure these embodied emissions. This offers an opportunity for innovative research to make a difference to the ability of the construction industry to address carbon emissions more holistically. The industrial sponsor, AECOM, has supported this research as a direct consequence of its work in addressing embodied carbon and resource efficiency in the built environment. The most recent example of this work has been the CIBSE technical memorandum on 'Resource efficiency of building services' (CIBSE, 2014a). And as discussed later in section 2.3 of the literature review, estimation of embodied carbon can be used as a proxy to measure progress towards several activities associated with making the built environment more environmentally resource efficient.

To meet these challenges, it will be critical that the metrics underlying any tools used to estimate embodied carbon for practitioners working with building services systems address uncertainty, whether the tools are manual reference guides (RICS, 2010, 2014, 2017) or software solutions (Etool, 2018). The definition of uncertainty and how it might be addressed with respect to the research problem is explored in more detail in the literature review in the next chapter.

1.4 Aims and objectives

The aim and objectives of the research reported in this thesis were informed by the literature review presented in chapter 2 and a series of scoping interviews conducted in the first six months of the research and summarised in Appendix 2. They are as follows:

Aim: To investigate and enable a better understanding of the embodied carbon impacts of building services systems in commercial office buildings and the effects of uncertainty on estimation of those impacts. In order to address this aim the study incorporates the following series of complementary objectives:

Objectives:

RO1 *To identify a range of barriers and drivers that inform industry practice on the calculation and reduction of embodied carbon in building services systems;*

RO2 *To develop an estimation method for embodied carbon of composite building services components that addresses uncertainty of input parameters;*

RO3 *To apply the estimation method to the comparison of embodied carbon impacts of alternative building services systems, initially focusing on heating, ventilation and air-conditioning (HVAC) systems;*

RO4 *To identify and explain the decision-making processes involved in selecting options for the design of HVAC systems for office buildings.*

RO5 *To produce a specification for a tool for practitioners to compare HVAC systems using embodied carbon.*

1.5 Research topics needing further investigation

In Figure 1.2, the background to the research problem as described so far is illustrated. Four key concepts, shown by the numbered text boxes, describe background topics that influence the processes and outcomes of measuring carbon emissions associated with building services. These are global drivers; UK drivers and barriers influencing construction industry practice; calculation methods, data and tools; and decision-making in building design. The three text boxes placed below the concepts numbered 2-4 summarise areas in the research literature requiring further investigation with respect to embodied carbon and building services. Each of these topics has informed one or more of the research objectives of this study. Topic 2 informs the first research objective, topic 3 informs the second, third and fifth research objectives and topic 4 informs the fourth and fifth research objectives.

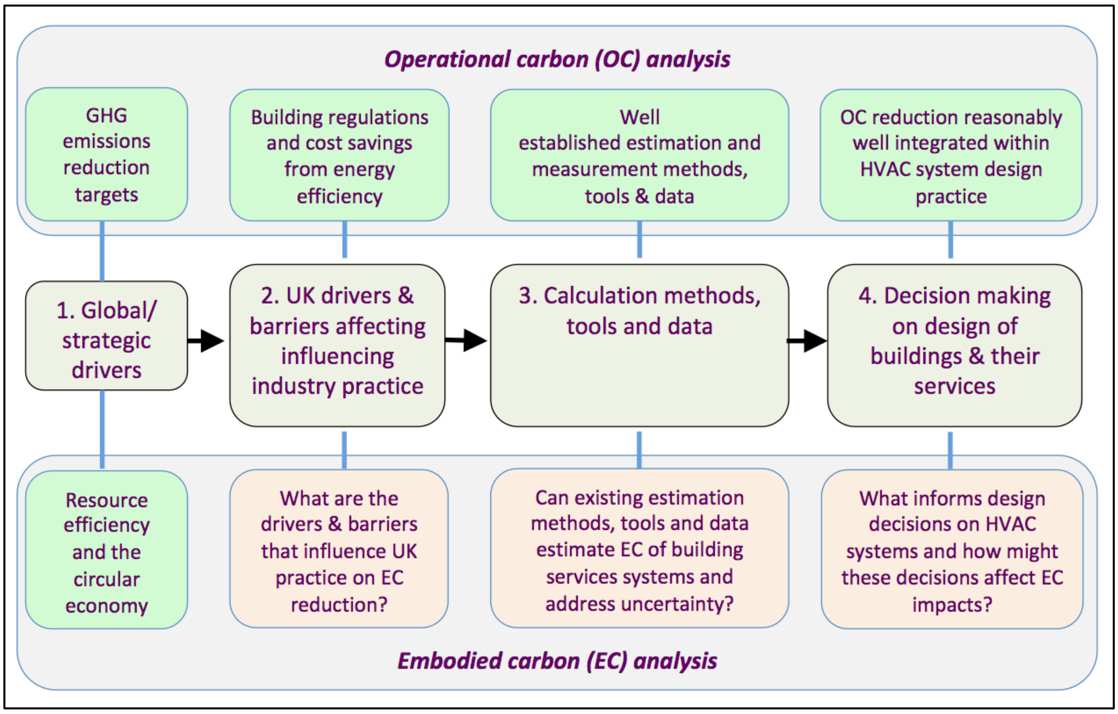

Figure 1-2: Research topics needing further investigation

1.6 Research design

The research design developed for this study is grounded in environmental life cycle assessment (LCA), a broad discipline based philosophically on positivism but also informed by 'post-normal' science (Lazarevic et al, 2012). It is implemented using a complex, mixed methods research design in phases with sequential, nested and concurrent features, utilising integration of data types, data collection methods and data analysis. Three main phases of primary research are conducted. A survey of construction industry practitioners is used to investigate the first research objective. This is followed by a series of empirical case studies of HVAC components and systems with which the second and third research objectives are investigated. A qualitative study of perceptions of practicing mechanical services engineers is then used to investigate the fourth research objective, after which a framework of business requirements analysis (Paul et al, 2014) is used to investigate the fifth research objective. A deductive approach is taken to theory development. The two areas of theory tested are:(a) Uncertainty propagation within environmental LCA; and (b) Rational choice and bounded rationality. The first informs the quantification of embodied impacts of HVAC components and systems and the second informs an understanding of decision-making on HVAC systems design as applied to commercial office buildings in the UK.

1.7 Intended contributions to knowledge

This study aims to contribute to existing knowledge with an integrated approach to address the multi-faceted research problem outlined in section 1.2.

1. The embodied carbon estimation method will apply a theoretical framework based on LCA and uncertainty propagation to a novel practical setting around estimation of embodied carbon impacts of HVAC systems in office buildings. The approach developed is intended to enhance the capability of embodied carbon analysis as a methodology to address the challenge posed by the limitations of deterministic estimation and gaps in material data for composite components and technical systems of building services.
2. The investigation of decision-making will apply descriptive and prescriptive choice theory to a novel practical setting of HVAC system design. Insight from this study and the survey of barriers and drivers

associated with embodied carbon in building services will be used to inform strategies for decision support on embodied carbon reduction.

3. Insight from the topics above will be used to support the specification for an estimation tool for HVAC systems that would enable practitioners to quantify the impact of specific embodied carbon reduction strategies such as product substitution, increasing material efficiency of a proposed design and product reuse.

1.8 Thesis Structure

The organisation of the thesis proceeds as follows from this introductory chapter:

Chapter 2 presents a review of literature informing the project background and scope, the areas of existing research in which greater knowledge is needed to address the problem space and the theoretical challenges associated with the problem space that have informed the research design. The topic of embodied carbon is also discussed within a broader context of the concepts of environmental resource efficiency and the circular economy. The review draws on a broad range of relevant literature including academic journal articles, industry communications and guidance, practitioner reports and policy documents.

Chapter 3 describes the research design in terms of six layers consisting of the philosophical paradigm, the approach to theory development, the methodological choices, the strategies of inquiry, the time horizon and the individual research methods. A series of research questions are identified matching the study's five research objectives and it is shown how the broad scope of the questions informs the choice of a complex, mixed methods research design with sequential, concurrent and nested features, located in a post-positivist research paradigm and with a deductive approach to theory development. The strategies of inquiry selected to address each of the research objectives are discussed and the choice of individual research methods summarised. The approach taken to integration of research findings obtained by mixed methods and addressing threats to validity is then discussed, after which a chapter summary is provided.

This is followed by three chapters of research findings. **Chapter 4** addresses research objective 1, exploring attitudinal, knowledge-related and technical barriers and opportunities associated with measuring the resource efficiency of building services, drawing on a web-based survey of 70 construction industry stakeholders based across the UK. The survey results demonstrate firstly that there is in principle support for activities to measure and increase resource efficiency of building services. The results also show that there are distinct perceptions on the relative importance of traditional and 'green' priorities during building design and on the effectiveness of various intervention methods to measure or reduce the resource impacts of building services.

Chapter 5 addresses research objectives 2 and 3. For the first of these, a case study-based method is used to estimate the embodied carbon impacts of HVAC components and compares the effectiveness of analytical and sampling-based methods to propagate uncertainty of input parameters. It is demonstrated that parametric methods can predict the embodied carbon impact of generic building services components based on information on raw material type, component mass and rated power output and that these methods can be made more robust if combined with uncertainty propagation and sensitivity analysis. A method of analytical uncertainty propagation based on first-order Taylor-series approximation is tested against a sampling-based method, Monte Carlo Simulation. The analytical method is found to be computationally more efficient than the sampling-based method, whilst in most circumstances equally robust, in identifying whether uncertain input parameters can significantly affect the reliability of estimates of embodied carbon for HVAC components. To address research objective 3, the two methods are tested again in a comparison of alternative HVAC systems by their embodied carbon impacts, incorporating the effect of uncertain input parameters. Results are presented for a base-case comparison between four case studies of air-conditioning systems that each use one of three alternative technologies, which are fan coil units (FCU), variable air volume (VAV) and variable refrigerant volume (VRV). The results show that technological differences between systems can mean that their embodied carbon impacts are significantly different even when input parameter uncertainty is present.

Chapter 6 addresses research objective 4 by investigating decision-making in the design of HVAC systems for office buildings. This is done using a qualitative study based on semi-structured interviews with 19 building services engineers based in three UK regions. The results of these interviews are analysed thematically and critically to test the experience of participants against the theories of, firstly, rational choice and secondly, a group of theories based on bounded rationality. Aspects of these theories are found to provide a more consistent explanation of decision-making activities participants than rational choice, In particular, heuristics that may help or hinder decision-making are identified, a possible 'status quo bias' is identified as a way to explain the relatively low perceived importance of embodied carbon within the construction industry and the use of 'framing' is found to provide a possible explanation for the inclusion or exclusion of embodied carbon as a consideration in decisions on HVAC design. These theoretical lenses enable a wider range of decision support measures to be identified than those that would meet the needs of a decision maker under rational choice. The results also indicate how the implementation of embodied carbon estimation tools can be made more effective if aligned with the real-world strategies of stakeholders.

Chapter 7 addresses research objective 5 by combining results from the previous chapters using a framework of business requirements analysis to deliver a specification for a selection tool to compare HVAC systems by their embodied carbon impact. A business process model of the functions of the proposed system is outlined, based on system requirements drawn from the estimation method developed in chapter 5 and the user needs identified in chapter 6. Worked examples are presented of the calculations that would need to be performed by the system and a forward strategy is outlined for the future development of the tool to encompass a wider range of building services and to draw on a larger evidence base of case studies.

Chapter 8 reviews the research problem addressed by the study and then discusses the implications of the findings for existing knowledge in terms of theory, methodology and practice. This is done in relation to the main topic, embodied carbon estimation, as well as the secondary topic, decision-making in HVAC design. After this, the contributions to knowledge are summarised. Novel features of the embodied carbon estimation method are identified to include (a) its focus on two relatively unexplored areas, building services systems and uncertainty analysis; (b) an iterative approach to combining uncertainty analysis and uncertainty reduction; and (c) the use of an analytical method of uncertainty propagation to provide a computationally efficient result. Key features of the analysis of decision-making are identified to include (a) the finding that the interaction between classically rational and boundedly rational behaviour in each decision-making environment is inherently uncertain; and (b) the finding that framing may inform barriers as well as enabling features associated with decisions to reduce embodied carbon in building services.

Chapter 9 begins by identifying key findings in relation to the research aim and objectives and related research questions. Limitations of the study are then discussed, addressing methodological threats to validity and practical challenges in data collection. Alternative approaches that may have been used within the research design are then discussed in respect of LCA methodology and uncertainty analysis, after which the research findings are summarised and recommendations made for further work in relation to the research objectives.

2 Literature Review

2.1 Introduction

This chapter presents a review of literature forming the knowledge base for the project background and identifies the topics within the problem space that require further investigation. The chapter begins with a review of the background to the research problem, after which a critical review follows of theoretical and practical aspects of the research problem within the relevant research literature, both industrial and academic. Consideration is then given to the theoretical challenges entailed in addressing these topics, ending with a summary of areas covered, showing how the study objectives are focused on the key topics of inquiry being examined.

2.2 Policy context for embodied carbon

This section considers firstly the policy arguments for measurement and reduction of embodied carbon in the built environment and secondly the current state of public policy as implemented in this area.

2.2.1 Supporting emissions targets

The significance of the built environment in humanity's use of environmental resources is recognised and highlighted by the Sustainable Buildings and Climate Initiative of the United Nations Environment Programme (UNEP), which notes that 'the buildings and construction sectors account for 40% of global energy use' (and) '30% of energy-related GHG emissions' and that sustainable buildings can 'improve the social, environmental and economic performance of cities, regions and nations' (UNEP 2016, page 3). In responding to this challenge, the second implementation period of the Kyoto Protocol has, since 2008, involved legally binding national commitments on developed countries to reduce GHG emissions (United Nations Framework on Climate Change, 2018). UK commitments on GHG reduction also have a legal basis in the national 2008 Climate Change Act, which requires that net annual GHG emissions by 2050 must be at least 80% lower than a 1990 baseline (Climate Change Act, 2008). The UK's ratification in 2016 of COP-21, the Paris Agreement on climate change, also requires 'net zero' GHG emissions across the UK economy by the second half of the 21st Century (CCC, 2016). At a more detailed level, the 5th UK Carbon Budget, agreed in 2016, requires UK GHG emissions to be cut by at least 57% from 1990 to 2030 and by 26% from 2016 to 2030 (CCC, 2017), whilst the 'Construction 2025' strategy, produced in 2010, sets a target of emission reductions within the UK built environment of 50% by 2025 against a 1990 baseline (HM Government, 2010).

Whilst these emissions targets seem clear, the UK's current and anticipated progress in meeting them has been challenging. The Committee on Climate Change estimated in 2017 that currently agreed UK Government policies would at best deliver only half of the GHG emissions reductions needed by 2030 (CCC, 2017), and would fall short by around 100 Mt CO_2e. If the definition of built environment emissions is limited to direct, operational emissions from buildings, which were 88.6 Mt CO_2e in 2016, representing 19% of the total UK territorial emissions of 466 Mt CO_2e that year as defined by the UK GHG inventory, the shortfall in reductions of these emissions by 2030 was estimated to be 19 Mt CO_2e (CCC, 2017).

However, total GHG emissions from the built environment may also be defined to include indirect operational emissions from the generation of electricity used in buildings, which amounted to 52 Mt CO_2e in 2016 (CCC, 2017) and product-stage embodied emissions from the construction supply chain. It should be noted here that these embodied emissions are not specifically identified within the categories used by the official territorial UK carbon accounts that are reported to the European Union and the United Nations Framework on Climate Change (UNFCC), (BEIS, 2018). This is partly because the territorial carbon account groups emissions by the broad industrial sector in which they are produced, rather than by counting emissions within the supply chain of particular products, which would be necessary to quantify embodied emissions. Therefore a brief examination of the estimated total value of embodied emissions in the UK built environment is useful here to evaluate the contribution that reductions in embodied carbon can make in meeting GHG emissions targets.

While this research focuses on estimation of embodied carbon at building level using process-based LCA methods, other studies have considered the total value of embodied carbon in the UK built environment using an economic input-output based LCA approach (see for example HM Government, 2010; Department for Business, Innovation and Skills, 2010, Giesekam et al, 2014; Green Construction Board, 2013, 2015). According to those studies, embodied carbon makes up between 17-22% of all carbon emissions associated with the built environment depending on the base year of each study and amounts to between 35-52 Mt CO_2e. These studies define embodied carbon to include emissions associated with building design but exclude emissions associated with product replacement, but they include all other life cycle stages of the broader definition of embodied carbon described earlier in section 1.1. Findings indicate that although roughly half of the embodied emissions in UK construction are estimated to be associated with imported products (Giesekam et al, 2014) and would not form part of the UK's territorial emissions, the UK would need to reduce embodied carbon in both domestic and imported construction products to avoid 'weak carbon leakage'. This can happen when increased consumption of imports from countries not included in Annex 1 of the UNFCC raises net emissions in global supply chains (Barrett et al, 2013). To reduce embodied emissions of construction products as designed and installed in UK buildings requires the ability to identify the embodied impact of potential design options, a task that in turn requires the robust methods, tools and data that are the focus of this study.

Another policy argument in support of reducing embodied emissions relates to the 'time value of emissions', which refers to the difference in value to society between emissions in the present and future (Marshall and Kelly, 2010, Darby, 2014, Karimpour et al, 2014). This approach relies on the proposition that the social cost of a physical unit of carbon dioxide emitted or saved in the present is greater than that of the same amount emitted or saved in 50 years' time, because of its impact on limiting global warming to a pathway defined by emissions targets in order to avert a climate catastrophe. When considered in relation to carbon emissions associated with buildings, the time value of emissions is also affected by future trends towards decarbonisation of electricity grids and energy efficient equipment, the rate of decay of atmospheric CO_2 and an economic discount factor (Darby, 2014). The net effect is that the ratio between estimated product stage embodied carbon and operational carbon over a given building lifetime is higher than it would be if the time value of emissions was not considered. Therefore embodied carbon can represent a higher share of lifetime building emissions and its mitigation in the present can be seen to have a greater value to society than would otherwise be the case.

2.2.2 Current policy on embodied carbon in the built environment

Although compulsory building regulations in the UK have not to date required measurement or reduction of embodied carbon, recent developments suggest that embodied carbon has acquired greater importance within built environment policies globally (De Wolf, Pomponi and Moncaster, 2017). Indications of this process include the publication of standards prepared by European technical committee CEN/TC 350 for building-level LCA studies (BSI, 2011) and environmental product declarations (EPDs) about construction products, (BSI, 2014). Embodied environmental impacts have also gained importance within voluntary building environmental assessment (BEA) schemes, a fact illustrated by a rise in the relative weighting given to credits related to building materials in BREEAM UK New Construction scheme, from 12.5% in 2011 to 13.5% in 2014 and 15% in 2018 (BRE Global, 2016a, 2016b, 2018). The 2018 scheme also requires the LCA credit 'Mat 01', which is worth up to 60% of all the material credits, to be met by a quantitative life cycle assessment. This eliminates an alternative route to obtaining the LCA credit prior to 2018 that had only entailed specifying approved products from the BRE 'Green Guide to Specification'. There is evidence that BEA schemes incentivise the design and construction of green buildings due to the market effect of favourable scheme ratings on property prices (Chegut et al, 2014, Oyedokun, 2017), but it is not yet clear whether the availability of credits associated with material efficiency and LCA have led to an overall reduction in embodied impacts of new buildings as built.

At national level, a UK government recommendation made in 2010 by the Low Carbon Innovation and Growth Team (LCIGT) to require whole-life carbon appraisals for all publicly funded capital projects has not yet been implemented (HM Government, 2010). The current UK Clean Growth Strategy (HM Government, 2018) makes no mention of reducing embodied carbon, possibly because it considers GHG emissions on the territorial basis, which as discussed earlier in section 2.21 does not use embodied emissions as an accounting category. Therefore 'energy efficient commercial and industrial buildings' are only mentioned with regard to operational energy and emissions (HM Government, 2018, p67). Regionally, more progress is being made in planning policy, as exemplified by the draft London Plan, which states that 'whole life carbon assessments are… required for development proposals referable to the Mayor' (GLA, 2018, s.9.2.9a). However, the Plan also defines embodied carbon to cover the 'collection, manufacture, assembly, recycling and disposal' stages of a product (GLA, 2018, Annex 3), a list that excludes recurring impacts from the maintenance, repair, replacement and refurbishments stages (identified respectively by modules B2-B5 in the TC 350 standards (BSI, 2011, 2014)). Similarly, it is also the case that the term 'whole-life' when applied to carbon emissions of buildings has differed somewhat in the scope of life cycle stages covered when used by the LCIGT (HM Government, 2010), the TC 350 standards (BSI, 2011, 2014) and the GLA (2018). For clarity, all subsequent references to 'whole-life' carbon in this study will refer to the stages covered by TC 350 modules A-C, which are illustrated later in Figure 2.2.

Elsewhere in Europe, a few examples have emerged of building regulations requiring the measurement and/or reduction of embodied carbon (Bionova, 2018). The Dutch building regulations have since 2013 required an LCA calculation for new buildings above a minimum size, using a weighted score of 11 environmental impact categories including GWP, although no limits are set for the planned impacts and this is seen to have hampered compliance (Klijn-Chavelerias and Javed, 2017). A French pilot scheme began in 2016 for a draft energy and environmental regulation planned for implementation in 2020, in which whole-life carbon and energy assessments of new buildings are linked to incentives for reduced impacts (Ministère de la Transition Écologie et Solidaire, 2019).

An important feature of both the Dutch and French regulations is that the methodology in each case requires product stage impacts of a comprehensive range of building services systems to be measured (Stichting Bouwkwaliteit, 2014, Ministère de la Transition Écologie et Solidaire, 2017). In comparison, BREEAM UK New Construction has only introduced an exemplary LCA credit for 'core building services' in its 2018 version (BRE Global, 2018), while previous versions of the scheme only applied LCA assessment methods to the building structure and envelope. It can therefore be concluded that policy measures to measure and reduce embodied carbon, both for buildings overall and specifically for building services systems, have evolved further outside the UK than domestically. However, it is also true that neither compulsory policies nor the market effect of BEA schemes in the UK appear so far to have driven the reduction of embodied carbon to become a priority in building design practice.

The improvement of embodied carbon estimation methods has value not only in the context of supporting the aim of reducing GHG emissions, but can also support the wider aims of resource efficiency and the circular economy. These aims have provided the initial motivation for this research, via a report supported by the project sponsor into 'resource efficiency of building services' (CIBSE 2014a). The report encouraged the construction industry to consider a broader range of whole-life environmental impacts of building services systems than the mainly operational energy and carbon impacts conventionally addressed in practice. The next section therefore defines building services, reviews the concepts of resource efficiency and the circular economy and their relationship to embodied carbon.

2.3 Embodied carbon, resource efficiency and the circular economy

An understanding of resource efficiency and the circular economy as aspirational goals in the design of building services systems helps explain the relevance of being able to measure embodied carbon in these systems. Building services engineering aims to 'provide a safe and healthy environment in which people can live, work and achieve' (CIBSE, 2017) and the types of services covered are illustrated in Figure 2.1. The rationale for considering resource efficiency of these services, as set out by the project sponsor, is that the concept of resource efficiency addresses a range of environmental impacts, particularly embodied impacts, of which awareness has been limited in the construction industry owing to the greater focus of UK policy and legislation on operational GHG emissions (CIBSE, 2014a).

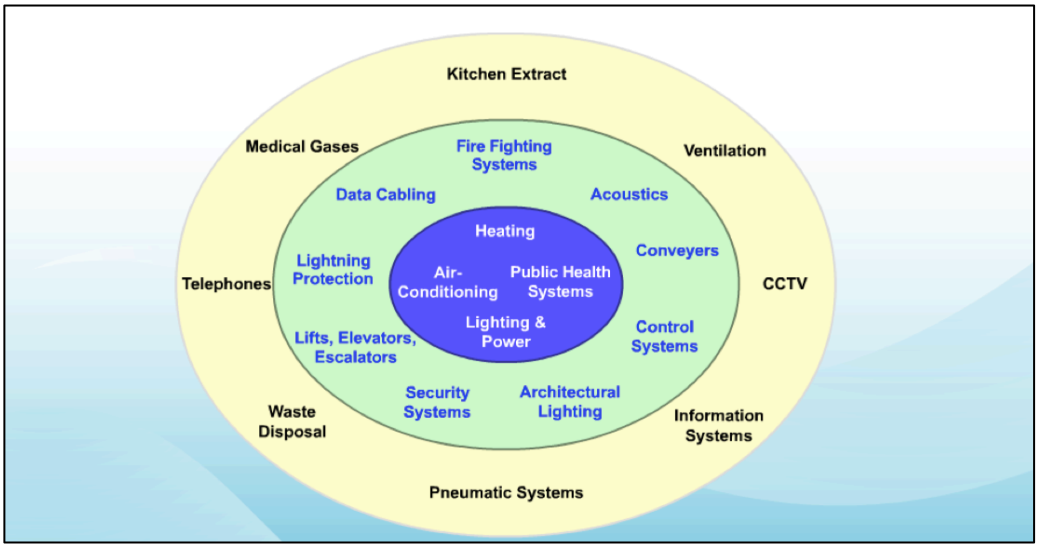

Figure 2-1: The scope of building services (CIBSE 2014b)

The concept of 'resource efficiency' has been defined as 'reducing the total environmental impact of the production and consumption of goods and services, from raw material extraction to final use and disposal' (UNEP 2010, p1). When applied to the built environment, it has been redefined as 'making best use of materials, water and energy over the lifecycle of built assets to minimise embodied and operational carbon' (WRAP 2017, p1). According to Geissdoerfer et al (2017) the circular economy (CE) is 'a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops' (p22). Thus while both concepts encompass more efficient use of key environmental resources, the CE arguably extends beyond resource efficiency, away from a 'linear economy' in which resources are 'extracted, used and thrown away', towards one in which resources are 'put back into the loop so they can stay in use for longer' (European Commission, 2017, p1). Despite this difference in emphasis, the two concepts entail similar activities at an operational level as shown in Table 2.1, which in both cases include reducing energy consumption, GHG emissions (both operational and embodied) and raw material usage.

Table 2-1: Activities involved in resource efficiency and the circular economy

Definition of resource efficiency in construction (WRAP, 2017)	'Key characteristics and enabling factors of a circular economy' (EEA, 2016)
• Reducing materials consumption and wastage; • Increasing reuse and recycled content, and enabling reuse and recyclability at end of life; • Matching the durability and lifespan of assets to service life; • Using resources with no scarcity and source security issues; • Using products with lower embodied carbon and embodied water; • Reducing energy and water use during construction; • Enabling energy efficiency and water efficiency in use.	• Less input and use of natural resources; • Increased share of renewable and recyclable resources and energy; • Reduced emissions *(throughout the full material cycle);* • Fewer material losses/residuals; • Keeping the value of products, components and materials in the economy.

When viewed critically, neither resource efficiency nor the circular economy are linked to a single comprehensive method to measure progress towards impact reduction. The European Commission's initiative, 'Towards a Resource Efficient Europe', launched under its 'Europe 2020' strategy, offers no such assessment mechanism, although it accepts that 'the fact that resource efficiency requires action in such a broad range of areas means that modelling is particularly complex' (European Commission, 2011, p8). A literature review of 14 environmental assessment methodologies found that only two, of which one was

LCA, were suitable to measure progress towards the first four circular economy characteristics listed in the right-hand column of Table 2.1 (Elia et al, 2017). However, precise definitions of the circular economy remain vague, with another recent literature review identifying 114 alternative versions (Kircher et al, 2017). Therefore any ranking of assessment methodologies for their ability to measure such an ill-defined concept must be considered with care.

If LCA methodology has potential to measure some aspects of the circular economy and resource efficiency, does it also have value in measuring aspects of particular significance? It has been argued that embodied carbon can be seen as a 'proxy' for resource efficiency as it tracks energy consumed by resource impacts across the life cycle of materials (HM Treasury, 2013) and is expressed in GWP. This is illustrated by the fact that four of the seven mitigation activities defined by the WRAP definition of resource efficiency (shown in Table 2.1) are associated with reductions in embodied carbon – reducing waste and material consumption, increasing re-use and recycled content, matching the durability of assets to service life and using products with lower embodied carbon (WRAP, 2017). Besides this, LCA is philosophically based on the idea that energy and other elementary flows entering and leaving the system being studied are embodied in the life cycle of products (Lenzen et al, 2008). It follows that embodied energy or carbon analysis, which excludes other elementary flows, represents a subset of LCA (Moncaster and Symons, 2013).

One counter-argument to a focus on embodied carbon should be noted here, although its resolution is beyond the scope of this thesis. Whilst lowering embodied carbon can increase resource efficiency at project level by material substitution, using fewer materials, reuse or recycling, these activities do not guarantee a net increase in resource efficiency in the global economy. For instance, if a local decrease in demand for a particular product that may be high in embodied carbon is offset by increased sales of that product to other markets, there may be no net change in global resource efficiency in the supply chain of the product. To measure such an effect would require a 'consequential' approach to LCA, in which future consequences of decisions to reduce embodied carbon are measured, as opposed to the ‘attributional’ approach used in this study, that considers carbon emissions retrospectively within the time window of the product stage of building life (Buyle et al, 2013).

Having reviewed the background to this study, the rest of this chapter provides a critical examination of literature and theoretical questions associated with the research problem outlined in Chapter 1. This in turn provides the theoretical underpinning to the chosen objectives and research design.

2.4 Barriers and drivers influencing practice

In the absence of substantial regulatory policy or market drivers for embodied carbon reduction to date in the UK, the question arises of whether previous research can inform an understanding of barriers and drivers that inform industry practice on embodied carbon? Published research into general barriers and drivers affecting carbon reduction and other ‘green’ behaviour in construction has been informed by various theoretical and methodological approaches including a project management perspective (Zhang et al, 2015), socio-technical transition theory (Santos and Lane, 2017) and interpretive structural modelling (Abuzeinab et al, 2017). Many studies of barriers and drivers adopt a mixed methods approach in order to support practical policy arguments on how to change behaviour towards more environmentally positive outcomes (Tingley et al, 2017), especially where the focus is on specific green activities. To inform the present investigation, the question of whether previous literature on industry perceptions and practices has included embodied carbon in scope is relevant as well as the type of theory and research design used.

Relatively few extant studies include primary research with stakeholders on issues related to embodied carbon. A literature review on embodied and operational carbon in buildings cites barriers to embodied carbon analysis as including challenges with methodology and data collection, a lack of support from building regulations and a lack of interest from ‘public and industry stakeholders’ (Ibn-Mohammed et al, 2013). However none of the studies cited draw on primary research with stakeholders. A study of construction stakeholder views on general approaches to carbon reduction in Australia (Wong et al, 2013) surveys views of 107 construction industry respondents and measures statistically the association between drivers for carbon reduction, carbon reduction strategies and organisational culture of the firms surveyed. As embodied carbon reduction is only represented by one of 12 possible strategies, detailed conclusions cannot be drawn about barriers and drivers to specific activities involved. Another study on organisational barriers to carbon emissions reduction in the built environment in Hong Kong (Ng et al, 2013b) draws on 19 qualitative interviews with industry stakeholders in various roles. While a distinction is not always made between respondents' views on general and specific carbon reduction activities, the study notes that most construction contractors interviewed 'found it difficult to source green materials without knowing the actual performance and exact savings in carbon emissions involved' (Ng et al, 2013b, p122).

One of the few published studies focusing on UK construction industry attitudes to embodied carbon uses a mixed methods based survey to study barriers and drivers associated with the selection of low carbon materials (Giesekam et al, 2016). Key barriers were found to include lack of technical knowledge, negative perceptions by other professionals and lack of standards while key drivers included moral obligations felt by respondents, clients' wishes and the earning of credits in building assessment schemes. While this study provides valuable insight into views of respondents about the topics covered, the sample is said by the authors of the study to be unrepresentative of average industry attitudes as it targets 'early adopters' with 'extensive experience' in the use of low embodied carbon materials (Giesekam et al, 2016, p6). The study also focuses on raw materials used in the building envelope and structure and therefore does not provide information about attitudes towards embodied carbon in building services systems.

It therefore seems reasonable to conclude that further primary research with a broad sample of construction industry stakeholders, not overly skewed towards early adopters of carbon reduction, on the specific issue of embodied carbon in building services would add value to this study in providing insight into specific barriers and drivers influencing practice in this area.

2.5 Methods and data for embodied carbon analysis

This section considers the challenges inherent in available methods, data and tools for embodied carbon analysis of building services and how well existing industry standards and research literature have addressed these challenges. As established previously, the discussion treats embodied carbon analysis as being theoretically and methodologically based on environmental life cycle assessment (LCA).

2.5.1 The role of LCA standards

LCA methodology is based on the use of physical science to quantify environmental impacts and has evolved incrementally with the support of a series of ISO standards. These include generic standard for LCA studies (BSI, 2006a, 2006b) and standards prepared by European technical committee CEN/TC 350 for building-level assessments (BSI, 2011) and environmental product declarations (EPDs) about construction products, (BSI, 2014). While the TC 350 standards have enabled more consistency in building-related studies, all the ISO LCA standards still only represent a framework that allows much discretion on methods used to implement each study (Pomponi and Moncaster, 2017). Thus the findings of two LCA studies of the same building, product or service may not be comparable unless the methods applied in each case are comparable. Parity of methods has in general been more challenging for LCA studies of buildings than for LCA studies of common, mass produced products because buildings are relatively more unique, complex and varied in composition (Buyle et al, 2013, Cabeza et al, 2014). It should be noted here that variations in methodology between individual LCA studies can be seen as instances of uncertainty in the range of possible calculation models and/or scenarios adopted by each study (Huijbregts, 1998, Lloyd and Reis, 2007), therefore the use of ISO standards on LCA helps to reduce but not eliminate this kind of uncertainty.

An LCA study typically consists of four phases - the definition of a goal and scope, the life cycle inventory (LCI) analysis, the life cycle impact assessment and the interpretation (BSI, 2006). An embodied carbon study is effectively an LCA study that measures just one environmental impact, GWP, associated with carbon emissions, in the impact assessment phase. In order for the results of embodied carbon studies of buildings or building components to be comparable, the system boundaries and methods used for LCI analysis must be comparable and a common functional unit or functional equivalent needs to be used when making the comparison. The LCA ISO standards specific to buildings and building products have defined system boundaries for each stage of the building life cycle (BSI, 2011, 2014), but they do not specify which life cycle stages must be considered in the study. This means that an ISO-compliant embodied carbon study can include any combination of 13 numbered modules covering the product stage (A1-A3), the construction stage (A4-A5), the non-operational parts of the use stage covering maintenance, repair, replacement and refurbishment (B2-B5) and the end of life stage (C1-C4) (BSI, 2011). The modules are shown in Figure 2.2.

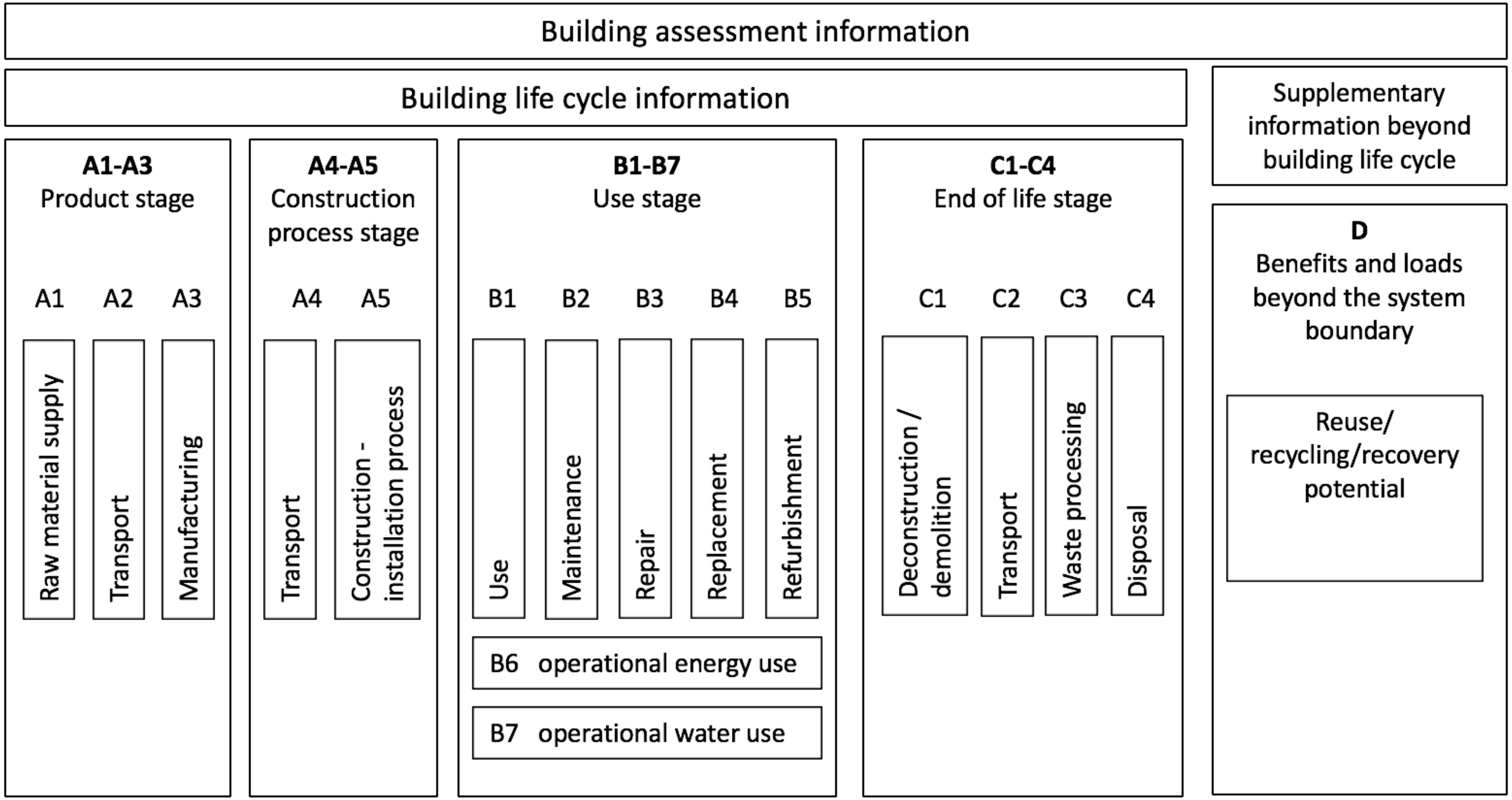

Figure 2 -2: Building life cycle information modules (BSI, 2011, 2014)

In practice, a recent literature review indicates that 98% of 80 embodied carbon building studies reviewed cover the product stage, with varying proportions of studies covering subsequent stages (Birgisdottir et al, 2017). This coverage is understandable as the manufacturing phase within the product stage is the most challenging to measure as it depends on data from the supply chain of each finished product. In principle, embodied carbon from the construction, installation and disposal of products can be measured in real time, while recurring embodied carbon depends on a combination of measurable real time data and product stage data.

Building-level LCA or embodied carbon studies are also allowed discretion by ISO standards on the physical boundary of building elements that are assessed in each life cycle stage. In particular, environmental impacts of the 'building integrated technical system', referring to the building services, must be included in assessment of the operational energy and water use of the building (stages B6 and B7), but do not have to be included in assessment of the product stage (stages A1-A3), covering raw material supply, transport and manufacturing (BSI, 2011, 2014). Other industry-led embodied carbon standards and guidance based on the TC-350 standards has emerged in the UK, but these also pose challenges for assessing the environmental impacts of building services. The RICS methodology to calculate embodied carbon until recently recommended excluding analysis of building services because they are 'complex to assess and their mitigation potential may be limited' (RICS, 2014, p16). A more recent RICS professional statement on whole-life carbon assessment, which is aligned with the ISO EN 15978 standard for life cycle assessment of buildings, lists building services among the building elements to be covered in a whole-life carbon assessment (RICS, 2017, p9). However, while building services are mentioned in relation to the life cycle stages for use, replacement, operational energy and operational water (B1, B4, B6 and B7), they are excluded from the discussion on building elements to be assessed during the product stage A1-A3 (RICS, 2017, p17) and from the list of 'minimum requirements' of building elements to be assessed over the whole building life (RICS, 2017, p8). As building services have been found by some studies to be responsible for 18-46% of embodied carbon over the lifetime of a building (Birgisdottir et al, 2017), the view from the earlier RICS standard that the EC mitigation potential of building services is 'limited' may not be entirely justifiable (RICS, 2014, p16), while the latest RICS standard does not make clear that calculation of replacement stage impact of building services depends on first knowing the product stage impacts (RICS, 2017, p21). Moreover, the enhanced definition of 'net zero carbon' proposed by UKGBC in order to embrace whole-life rather than just operational carbon emissions and carbon offsetting of buildings (UKGBC, 2019) uses the 2017 RICS standard as guidance for whole-life carbon assessments.

2.5.2 Variations in methods for life cycle inventory analysis

The other major issue in LCA methodology that affects embodied carbon studies of buildings, with particular implications for building services, concerns scope for variation in methods within the life cycle inventory analysis (LCIA) stage. The variations in methods of collection and calculation of input data are informed by the discretion within LCA standards as well as empirical variations in the availability and quality of data on buildings and building elements (Anand and Amor, 2017, Gavotsis and Moncaster, 2015). The TC-350 standards require a process-based analysis to be used for inventory data relating to building products (BSI, 2011, 2013a) although the generic LCA standards are not as prescriptive, therefore input-output based and hybrid methods can be used as alternatives (BSI, 2006a, 2006b, Birgisdottir et al, 2017). This can lead to model uncertainty between studies, because the results of studies produced by process and input-output or hybrid methods are not directly comparable, except where one study applies alternative methods to the same building and maintains consistency of other boundaries and assumptions (Ndungu and Molavi 2014). For building services components and systems, process-based analysis is arguably a more consistent method than input-output analysis because it is supported by a dedicated ISO standard for environmental product declarations (BSI, 2014) whose use is becoming widespread in LCA and embodied carbon building studies. However at least two examples exist of hybrid LCA studies that use U.S. input-output data to estimate the carbon intensities of building services components that cannot be found in European life cycle inventory databases (Whitehead et al, 2012. Poyry et al, 2015).

2.5.3 Challenges with benchmarking

The range of choice available in methods used for LCI analysis has led to significant variations between studies in the reported embodied carbon intensities of entire buildings (Birgisdottir et al, 2017) or common raw materials (Pomponi and Moncaster, 2017). Although this has been seen as a challenge for benchmarking purposes (Anand and Amor, 2017), average values of GWP per square metre of floor space (or per kilogramme of raw material) can be estimated across studies where reporting is transparent enough to permit adjustments for differences in data sources and study parameters. The situation is clearly more difficult for building services, where too few published LCA or embodied carbon studies exist to allow average GWP intensities per unit of floor space or system mass to be calculated for comparable product systems (Passer et al, 2012). This leads on to the issue of the availability of input data. This is a critical issue because variations in the source, quality and reliability of available data can be a source of parameter uncertainty within an LCA or embodied carbon study.

2.5.4 Environmental Product Declarations and life cycle inventory databases

Product stage data for a system of building services should include the amount and type of each raw material in each component and the associated cradle to gate GWP impacts. Under the standard ISO 15978, product stage data can be obtained from an environmental product declaration (EPD) for the specific product if one exists, a generic EPD or data set for a similar product, or a primary source such as a bill of quantities (BSI, 2011). However relatively few EPDs may be available for construction products used in the UK, as suggested by a recent embodied carbon study in which only 5 EPDs were found to match 200 products used in the design of a school building (Gavotsis and Moncaster, 2015). Of the publicly accessible Type III EPDs that meet ISO 15804, few cover building services components. Only 22, or 6%, of the 394 Type III EPDs accessible on the web-based international EPD database describe building services products, when searched in November 2017 (EPD International AB, 2017). This suggests that although earlier studies had anticipated that an increase in EPDs would resolve the lack of data on building services equipment (Passer et al, 2012), this has not happened. A further challenge is that the some EPDs compliant with ISO 15804 are not held on the international EPD database but stored separately on national databases and in many cases are not available translated into English, as is the case with the industry-led German database IBU (Institut Bauen und Umwelt e.V., 2019). Apart from EPDs, the main secondary data source for embodied carbon studies of buildings is life cycle inventory (LCI) databases. These include a thorough representation of simple construction materials such as steel and concrete but very few composite components used in building services (Hammond and Jones, 2011, Ecoinvent, 2018).

2.5.5 Results of studies comparing embodied and operational carbon

Comparisons between the relative value of embodied and operational carbon over the lifetime of a building are challenging because of several factors influencing the comparison. These include the time value of emissions, which was discussed earlier in section 2.2.1, the choice of building type, the assumed building lifetime, the country in which the building is located and other potential variations between estimation methods used by individual studies, as discussed in section 2.5.2. Notwithstanding these challenges, a review article sought to compare the findings of values of multiple research studies on operational vs. embodied carbon emissions and energy consumption (Ibn-Mohammed et al, 2013). A review of this comparison, amended to remove errors and references to articles no longer accessible, with added information on the building types used, confirms the extent of variation in values between and within studies, shown in Table 2.2. If the comparison is restricted to embodied carbon studies of office buildings in the UK, which is the building type considered by the present study, EC can make up between 37-68% of emissions over a 60 year building lifetime

(Eaton and Amato, 1998, Bailey, 2010). The variation in each case is due to the use of alternative scenarios. In the 1998 study the scenarios represent different combinations of building elements, while in the 2010 study they represent projections with and without the assumption of future grid decarbonisation.

Table 2-2: Studies comparing operational and embodied carbon and energy

Country	Author (date)	Relative value of embodied carbon (EC) and embodied energy (EE)	Building type
UK	Yohanis and Norton (2002)	EE is 67% of whole-life energy over 26 years	Single storey office
	Eaton and Amato (1998)	EC is 37-43% of whole-life carbon over 60 years	Small to medium office and large 8-storey office
	Smith (2008)	EC is 80% of whole life-carbon over unspecified period	N/A
	Bailey (2010)	EC is 42-68% of whole-life carbon over 60 years	20-storey office
US & Canada	Ayaz and Yang (2009)	EE is 11-50% of whole-life energy over 60 years	'Typical' office building
	Webster (2004)	EE is 2-22% of whole-life energy over 50 years	Multiple building types
Sweden	Thormark (2002)	EE is 40% of whole-life energy over 50 years	Residential
Israel	Huberman and Pearlmutter (2008)	EC is 74-79% of whole-life carbon and EE is 53-67% of whole-life energy over 50 years	Residential

2.5.6 Results of embodied carbon studies on building services

Because of the gaps in environmental product declarations and life cycle inventory databases, published LCA or embodied carbon studies that include or focus mainly on building services using process-based analysis have relied on one or more of the following, subject to availability:

(a) Primary data on mass and energy inputs from product manufacturers;

(b) Estimated or measured material quantities from design drawings, building information models (BIM) or bills of quantities; and

(c) Secondary life cycle inventory data for upstream processes in the supply chain of individual raw materials.

While too few of these studies exist to support robust benchmarking of EC values of generic components or systems, their findings highlight a number of issues that are useful in informing the development of EC estimation methods.

Table 2-3: Embodied carbon studies of building services in office buildings

Source	Total EC (kg CO_2/m^2)	Floor area	Building services EC (kg CO_2/m^2)	Services EC as % of total	Description of building and life cycle stages covered
AECOM (2012)	539.2 - 1620 (Average = 954.8)	GFA	7.8 - 274 (Average= 127.5) (Average for HVAC = 56)	1.4 - 16.9 (Average= 13.3)	Average of 30 office buildings, mostly fully serviced, with average 11.5 storeys, stages A1-A3
WRAP (2011)	1104	N/A	132	12	Notional fully serviced medium rise large office building, stages A1-A3
Halcrow Yolles (2010)	757	GFA	8 - 33.3 (Average = 20.7)	1.5 - 4.1 (Average = 2.6)	Average of 3 low rise office buildings with natural ventilation, stages A1-A3
Franklin & Andrews (2010)	883.5	N/A	53	6	Notional office with natural ventilation, stages A1-A3
Chen et al (2012)	N/A	N/A	8.7-39.7 (HVAC only)	N/A	Comparison of 3 HVAC system options for educational building, 13 storeys, stages A1-A3
Kaspersen et al (2016)	N/A	GFA	47-53 (HVAC = 35-38)	N/A	Comparison of building services of 8 or 12 storey office & health care building, stages A1-A3

The first issue concerns variations in academic content, methodology and reported results. Of the five sources summarised in Table 2.3, only one is in a peer-reviewed academic journal (Kaspersen et al, 2016). Other peer-reviewed LCA studies of installed building services systems exist, but their results cannot be interpreted in terms of GWP impacts because impacts are assessed using a weighted, single-score method, Ecoindicator-99 (Prek ,2004, Heikkila, 2004, Chau et al, 2007). Two of the sources in Table 2.3 are benchmark values within industry reference publications with limited information on the inventory data used for the calculations (WRAP, 2011, Franklin and Andrews, 2010). The other three references in Table 2.3 are empirical case studies in which systems of building services are compared across a single building (Chen et al, 2012) or multiple buildings (AECOM, 2012, Halcrow Yolles, 2010). Based on all six sources in Table 2.3, product stage embodied carbon impacts of building services can vary much between office buildings, from 7.8-274 kg CO_2e/m^2, making up between 1.4 - 16.9% of product stage EC impacts of the entire building for studies in which other building elements apart from services are counted. An understanding of the factors responsible for these variations is critical to the design of strategies to reduce EC in building services, but the limited scope and number of published studies available suggests that this requires further research. In principle, some of the variation can be explained by the level of servicing per building, as was the case within the AECOM study which included in its sample buildings with natural as well as mechanical ventilation (AECOM, 2012). Other sources of variations in EC associated with HVAC systems might include differences between systems used in buildings by type and differences in the spatial layout of systems and building form between building.

A secondary issue affecting academic research on embodied carbon in building services is transparency. Parametric studies that compare embodied carbon impacts of alternative building designs by changing selected parameters to vary the servicing systems away from a base option do not always state the source of the LCI data on the building services (Ruuska and Hakkinen 2014) or report the results in a way that enables initial and recurring embodied carbon to be valued separately (Basbagill et al, 2013, Hawkins and Mumovic, 2017). Thirdly, studies in which GWP per square metre of gross floor area (GFA) is compared for different building elements may understate impacts of building services. This is because building services tend to be sized by designers based on net rentable or lettable area, a value that excludes landlords' areas and plant rooms and is therefore normally smaller than GFA (Kaspersen et al, 2016). These three issues - (a) variations between studies in quality, methodology and values of reported EC for building services; (b) a lack of transparency of methodologies used; and (c) the effect of multiple measures of floor space - also illustrate uncertainty between the calculation methods used by different embodied carbon studies, a topic that is discussed later in this chapter.

With these qualifications in mind, parametric methods of embodied carbon estimation appear to be the most appropriate way to redress the shortage of data on building services in accessible EPDs and LCI databases. One such method was proposed to estimate embodied impacts of composite components of different sizes, based on multiplying known embodied carbon values of generic base components by a 'defining metric' such as rated power output (Moncaster and Symons, 2013, p519). Ideally this should be extended to address assembled systems of building services for an entire building, which would require representative data to be compiled for component type, mass and embodied carbon of identifiable generic systems, whilst including a means to address parameter uncertainty about the numerical values of input data.

2.5.7 Embodied carbon estimation tools

As the topic addressed by this thesis is embodied carbon estimation for building services during early building design, there are implications for the use of estimation tools. The most detailed results can be obtained by specialised LCA software tools (Simapro UK, 2018, GABI, 2018), although these are complex and time-consuming to use and require a level of material detail not always available during early building design (Basbagill et al, 2013). Approximate LCA impacts can be calculated by whole building decision support software that comes with 'pre-defined building assemblies' (Athena Institute, 2017) and is less complex to use (Soust-Verdaguer et al, 2017), however the preset assemblies only cover major building elements and exclude services. As discussed earlier, there is some representation of embodied carbon or LCA based analysis within building environmental assessment (BEA) schemes such as BREEAM (BRE Global, 2018) and LEED (USGBC, 2013). However embodied carbon is not always assessed quantitatively and may still receive a lower share of scheme credit than operational carbon or energy impacts, as was found in a 2013 study (Ng et al, 2013a), even though as argued earlier its relative share has risen over time. For instance in the BREEAM UK New Construction scheme, the respective shares of credits on energy and materials have gone from 19% for energy and 12.5% for materials in 2011, to 16% for energy and 15% for materials in 2018 (BRE Global, 2016a, 2018).

Even where quantitative assessment is used to estimate embodied carbon within a BEA scheme, few scheme credits may be available for assessment of building services. One exception to this picture is that the BREEAM UK New Construction scheme now offers an exemplary credit for approved LCA studies of 'core building services options during concept design' (BRE Global, 2018, p225), whereas previous versions of the scheme only offered LCA credits for non-services building elements.

2.5.8 Building information modelling (BIM) and embodied carbon estimation

An important development for the use of tools to estimate embodied carbon or other life cycle impacts in the built environment is the emergence of software that combines building information modelling (BIM) with simplified LCA (Capper, Matthews and Lockley, 2012, KT Innovations, 2017). This approach offers the promise that, assuming that LCI data of building materials, products and systems is available, the inclusion of such data into a BIM model of the physical building can enable design alterations to the model to be matched by instantaneous changes in calculated embodied impacts (Eleftheriadis et al, 2018). Meanwhile, some LCA studies are using BIM models only as a source for LCI data whilst conducting embodied carbon modelling with specialised LCA software (Kaspersen et al, 2016). However, a review of BIM-based LCA studies (Soust-Verdaguer et al, 2017) has found that most published case studies using combined BIM-LCA tools only consider embodied impacts of simple building materials, whilst 'building operations and processes' other than operational energy consumption are not considered. The embodied impacts of building services systems will therefore be excluded if the tool lacks input data on these systems. A related challenge for BIM-led EC estimation is that the quality and quantity of available LCI input data generally is lowest during early building design, when detailed information on materials is not known, although that is the time when the scope is greatest for substitution of low-carbon design alternatives (Peng, 2016). Given this background, it is relevant to consider the extent to which policy standards and market practice on BIM might enable or hinder the use of BIM to support estimation of EC impacts of building services.

In principle, if the physical attributes of all building components such as mass and raw material type were encoded in a BIM representation of those components, it would mean that material data for a building could be aggregated within BIM software and multiplied by the relevant EC coefficients to estimate EC impacts of the building or its sub-systems. However, details of constituent raw material types and masses needed to assess EC of composite building services components do not have to be routinely provided to comply with BIM standards. The ISO standard for BIM 'library objects', which represent types of product or product groups, states that the level of detail given in the attributes of such objects 'should be determined by their intended uses', but also should support 'assessment of economic and environmental impacts' and these *'may* [our italics] include initial (embedded) impacts or life cycle (in- use and end-of-life) impacts' (BSI, 2013, p2). In practice, BIM objects designed by component manufacturers or building services designers typically exclude these details, although CIBSE has proposed the inclusion of an 'embodied carbon' field in its proposed 'product data template' (CIBSE, 2019). Even if such a field were included, the fact that individual raw materials within a component do not have to be identified as attributes within its BIM representation would mean that calculation of the embodied carbon value for the component would require additional data on the type, mass and carbon intensity of each material.

At a wider level, UK government policy has promoted BIM as a means to achieve whole-life carbon emissions as well as savings in project costs and timescales (HM Government, 2013, 2015). However annual perceptions by construction practitioners on whether BIM will help achieve the government target of reducing greenhouse gas emissions in the built environment by 50% by the year 2025 (HM Government, 2013) have remained pessimistic. Annual BIM surveys conducted by RIBA Enterprises indicate that between 2015 and 2018, a majority of over 800 survey respondents believe either that BIM will make no difference in reducing GHGs or that it will hinder achievement of the target, although the proportion holding these views has fallen from 59 to 54% (RIBA Enterprises, 2015; 2018)

With regard to embodied carbon estimation of building services systems, it can therefore be concluded that BIM-integrated tools have potential to support embodied carbon analysis but only if supplemented by appropriate data and/or metrics.

2.6 Addressing uncertainty

This section firstly considers general approaches to handling uncertainty in LCA research studies, after which it examines how uncertainty has been addressed in those LCA and embodied carbon research studies that consider buildings. A brief review follows of alternative methods of uncertainty propagation.

2.6.1 Classification of uncertainty in LCA studies

An established approach to classifying uncertainty in LCA studies states that uncertainty can exist in the models, scenarios or parameters used by these studies (Huijbregts, 1998, Lloyd and Reis, 2007). Model uncertainty concerns the mathematical relationships on which the models used by LCA methods are based. Scenario uncertainty exists because of the range of normative choices possible for the assumptions needed to design an LCA study, choices that include the boundaries, life cycle stages, functional units and allocation procedures to be used. Parameter uncertainty, the area on which this study focuses most, concerns the values of inputs such as material mass, energy use and emission coefficients for each process during the product life cycle. As categories to describe examples of uncertainty in an LCA study, the three types of uncertainty are not always mutually exclusive. A study of variations in LCA results obtained using five different life cycle inventory (LCI) databases to calculate impacts for the same three buildings found that differences between databases in values for the same process inputs as well as differences between impact assessment methods could affect results (Takano et al, 2014). The results could therefore be seen as subject to a combination of parameter and model uncertainty.

The established methods available to address uncertainty in LCA studies are considered to involve either reducing uncertainty or including uncertainty explicitly within the analytical model (Heijungs and Huijbregts, 2004). Reduction includes the 'scientific' approach of doing more research, the 'constructivist' approach of using expert elicitation to agree values for uncertain features of the problem; and the 'legal' approach of relying on default values for these features from authoritative bodies such as ISO, while inclusion of uncertainty uses statistical methods (Heijungs and Huijbregts, 2004). Therefore in an LCA or embodied carbon study one or more of these strategies can be adopted to address parameter, model or scenario uncertainty. The following are examples of each of the three types of uncertainty reduction:

- A study that uses empirical data from primary sources to quantify input parameters for a product system that is *either* not previously covered by research literature, *or* only covered by studies relying on secondary sources, is reducing uncertainty via additional measurement.
- Studies that use data from the Ecoinvent life cycle inventory (LCI) database are by default reducing uncertainty via a data quality matrix, which is a constructivist approach (Frischknecht and Rebitzer, 2005, Weidema and Wesnaes, 1996).
- EC studies of buildings that use the TC-350 standards (BSI, 2011, 2014) are reducing uncertainty by a legal approach.

However, there is no agreed position within LCA research about the extent to which each type of uncertainty reduction and uncertainty inclusion are alternative as opposed to complementary strategies. For instance, uncertainty inclusion via uncertainty analysis is presented as an optional element in the generic ISO LCA standard (BSI, 2006) but not mentioned in the standards specific to buildings and building components (BSI, 2011, 2014). Equally, compliance with the ISO LCA standards does not necessarily require uncertainty reduction by additional, empirical measurement of material input data, nor does it require that uncertainty analysis is used to quantify the extent to which uncertainty may have been reduced by the use of such measurement.

2.6.2 Uncertainty in LCA studies of buildings

A recent review article has shown that despite the existence of a considerable body of research literature on uncertainty in LCA, research studies applying LCA methodology or its sub-discipline of embodied carbon (EC) analysis to buildings have only rarely explicitly addressed uncertainty (Beltran et al, 2018). Whilst it can be argued that model and scenario uncertainty have implicitly been reduced by the 'legal' approach as implemented by recent ISO LCA standards for buildings and building products (BSI, 2011, 2014), uncertainty analysis of input parameters has seldom been applied to studies of buildings (Beltran et al, 2018). The dominant approach has been to use deterministic single-point estimates for calculated EC or other life cycle impacts of buildings, which implies ignoring the parameter uncertainty associated with life cycle inventory inputs. The risk here is that differences in values between estimated impacts of two alternative products can wrongly be assumed to be statistically significant if parameter uncertainty might render that difference insignificant. For instance, out of the twelve LCA or EC studies on building services considered earlier in section 2.5.6, of which eight were published in academic journals, all but three studies use a deterministic approach. The remaining three adopt a simplified approach to parameter uncertainty in which maximum and minimum values of input parameters are used to estimate a range of output values without a measure of dispersion based on a probability distribution (Basbagill et al, 2013, Ruuska and Hakkinen, 2015, Hawkins and Mumovic, 2017). Another approach to using uncertainty analysis in EC studies of the built environment is to quantify parameter uncertainty across secondary research sources by drawing an empirical probability distribution of EC coefficients used for structural building materials in previous LCA studies (Pomponi and Moncaster, 2017). This method could not be effectively be applied to building services systems, as too few peer-reviewed studies on building services are available to provide a representative sample, as discussed in section 2.5.3. Also, some of the variation in EC values between studies might be explained by variations in methodology rather than real differences in EC impacts. As such, these variations represent model and/or scenario uncertainty between EC studies. More robust approaches to uncertainty analysis exist in broader LCA research literature , and these are considered in the next section.

2.6.3 Approaches to the inclusion of parameter uncertainty

Explicit inclusion of parameter uncertainty into an LCA study entails the use of statistical methods, examples of which include sampling-based Monte Carlo (MCS) and Latin Hypercube simulation (LHCS), fuzzy set theory and analytical uncertainty propagation (AUP) (Groen et al, 2014). A review of uncertainty analysis in LCA studies identifies that uncertainty can be measured at various stages of the LCA model but has most frequently been addressed at the life cycle inventory stage; that the complexity of LCA makes it difficult to analyse all types of uncertainty within one study; and that the most commonly used methods of uncertainty analysis have been sampling-based (Lloyd and Reis, 2007).

Monte Carlo simulation, the most widely used sampling-based method, requires that pseudo random numbers are drawn from a set of input parameters with known probability distributions to produce a sampled distribution of an output parameter (Groen et al, 2014). Its accuracy is measured by the convergence rate between the sample mean and the true mean, using the standard error of the mean (SEM). The advantages of using MCS in LCA studies include its relative accuracy compared to other methods, its widespread availability within commercial LCA software, and its ability to make a nuanced comparison between environmental impacts of two products. The comparison is nuanced in the sense that it indicates the differences not only between the mean impact values of product A and B, but also between the probability distributions of each, enabling a full assessment of whether the difference between the values of impact A and B is significant. The main disadvantages of MCS are the large number of simulation runs needed, typically at least 1000 runs for each possible combination of all input parameters, and the difficulty in calculating the contribution of a single input parameter to overall output variance when there are a large number of input parameters (Heijungs and Lenzen, 2014).

By contrast, AUP is based on a method of calculus, first-order Taylor Series approximation. It has the advantage that it only requires a single calculation to estimate the contribution of each input parameter to output variance, regardless of the number of input parameters (Morgan and Henrion, 1990).

$$Var[y] \approx \sum_{i=1}^{n} Var[x_i] \left[\frac{\partial y}{\partial x}\right]_{X^0}^2 \qquad \text{(Equation 2.1)}$$

In Equation 2.1, the variance of output parameter y is shown to be approximately equal to the sum of the contributions to variance of each input parameter x, which in turn is expressed as the product of the input variance of x and the absolute value of the partial derivative of y with respect to x. In this form, this equation assumes there is no covariance between input parameters.
The disadvantages of AUP compared to sampling-based methods of uncertainty are firstly that it does not estimate a probability distribution for output uncertainty. Therefore, an LCA comparison between environmental impacts of two products could compare their mean values and rank their levels of uncertainty, but not fully compare the two probability distributions.
Secondly, AUP may be less accurate than sampling if input uncertainty levels exceed a particular threshold, which has been estimated by two recent comparative studies of AUP and sampling-based methods in LCA at a coefficient of variation of either 5% (Groen et al, 2014) or 10% (Heijungs and Lenzen, 2014). Lastly, if covariance exists between input parameters, a more complex calculation is required.

This discussion so far has outlined the gaps around the treatment of uncertainty in LCA and embodied carbon studies of the built environment and the range of approaches potentially available to address parameter uncertainty in such studies. However, existing comparative studies that test alternative methods of uncertainty propagation based on established statistical theory (e.g. Groen et al, 2014, Heijungs and Lenzen, 2014) have used notional or artificial case studies rather than practice-based examples associated with the built environment. Given this background, the testing of AUP against a sampling-based propagation method in a practice-based embodied carbon study of building services systems would offer a tangible contribution to the research literature in this area.

2.7 Design choice in HVAC systems

Given the need to investigate the process of making decisions on the design of HVAC systems as outlined in section 1.2, an understanding of such a process should be informed by empirical study of design practice as well as relevant theory, to ensure that the estimation tool is not based on unsupported assumptions about how and why designers make choices. Concerning theory, academic and technical reference literature on decision support for engineers in HVAC system design is often based on an implicit, positivist assumption that decision-makers act rationally to maximise utility when choosing options (CIBSE 2016). This is reflected by the pre-eminence of multi-criteria decision making (MCDM) as an analytical framework in this area (Shahrestani et al, 2017).

Expressed formally, the theory of rational choice assumes not only the maximisation of utility, but also (a) completeness and transitivity of alternative choices; and (b) the independence of irrelevant alternatives (Coleman and Fararo, 1992). Completeness means that the decision maker has perfect knowledge of all available choices. Transitivity means that if choice A is superior to choice B and choice B is superior to choice C, then choice A must be superior to choice C. The independence of irrelevant alternatives means that if a particular choice is selected because it satisfies the first two assumptions, the selection will not be affected by removing any of the other available options. If these strict assumptions are not accepted as reflective of behaviour in the real world, a range of alternative ontological positions have been developed to explain how decisions are made, each using varying degrees of heuristics or intuition (Huffrage and Marewski, 2015). Among these, one approach that may suit an engineering context is the theory of bounded rationality, in which decision makers practice 'satisficing' or search for cues to inform their choice, with simplified rules or heuristics for searching for options, stopping the search and making a final decision (Simon, 1981, Gigerenzer, 2002).

Bounded rationality can also be seen as a broad framework informing a group of more recent 'descriptive' decision theories based on observations of decision-making *in practice*, all of which represent alternatives to the 'prescriptive' theory of rational choice, which describes how decisions *ought* to be made based on a normative model (Beach and Connolly, 2005, pp. 11-12). Descriptive theories include naturalistic decision-making (Klein, 2017), heuristics and bias (Tversky and Kahneman, 1974) and fast and frugal heuristics (Hafenbradl et al, 2016). In these perspectives, decision-making involves a stage of diagnosis before possible actions are selected and then implemented, with a key aspect of diagnosis being 'framing', defined as 'embedding observed events in a context that gives them meaning' (Beach and Connolly, 2005, p16). Framing may precede or form part of heuristics that can guide the choice process and is also used in a prescriptive theory, prospect theory, to explain how perceived losses or gains in the way that choice options are presented can alter decision- making behaviour (Beach and Connolly, 2005, p89). While descriptive theories vary in detail, they broadly accept that conditions of bounded rationality arise from cognitive biases of actors as well as contextual constraints in the decision environment. Depending on the theory used, the use of framing and heuristics in decision- making may either be seen as sources of cognitive bias (Tversky and Kahneman, 1974) or as ingredients in quick and effective decisions by experts (Hafenbradl et al, 2016, Klein, 2017).

Studies applying descriptive theories to the construction industry have been relatively scarce, although an extensive body of research informed by descriptive theories exists in relation to other decision making environments. One study examining UK construction practice suggests that bounded rationality tends to influence decision-making negatively against energy efficient choice (Sorrell, 2003) and that an understanding of bounded rationality should therefore inform policy designed to change behaviour. By contrast, a broader study of the 'fast and frugal' view model which does not draw on examples from construction suggests that greater efficiency in decision-making may be intrinsic to bounded rationality (Hafenbradl et al, 2016). Some descriptive studies on HVAC design include heuristics to model practitioner behaviour (Maor and Reddy, 2004) but do not consider psychological factors that may inform the heuristics used by practitioners, examples of which might include satisficing in a bounded rationality approach or intuition and/or emotion in other theoretical approaches.

As the Sorrell study did not draw on primary research with practitioners and more recent research on bounded rationality in construction practice appears to be scarce, there is a case to be made for further investigation of how design teams make decisions about HVAC systems and whether the concept of bounded rationality can help explain the choices of decision makers. In particular, if bounded rationality and associated descriptive theories can explain design decisions in practice that do not meet the criteria for rational choice, this may also help identify features within the decision-making environment needed to support decisions towards embodied carbon reduction.

2.8 The scope for embodied carbon reduction

While this chapter has mainly considered ways to measure embodied carbon in building services systems and the barriers and drivers influencing practice in this area, it is also important to note that the scope for reducing embodied carbon in practice is highly dependent on both these topics. Once the embodied carbon value of a potential design option can be quantified, various strategies are available that echo and expand upon the WRAP activities to increase resource efficiency that were listed earlier in Table 2.1 (WRAP, 2017). Equally, in order for policy and market drivers to incentivise embodied carbon reduction it must be feasible to quantify possible reductions in terms of design choices. A recent review of 80 international building case studies for reducing embodied energy and GHG emissions identified 11 reduction strategies (Malmqvist et al, 2018). These are as follows:

- Using timber structures
- Using other ‘natural’ materials
- Using recycled and reused materials/components
- Using new, innovative materials/components

- Light weight construction
- Optimising building form and design of lay-out plan
- Building/service life extension
- Reusing building structures
- Flexible/adaptable design
- Reducing construction stage impacts
- Reducing end-of-life impacts

Apart from the first two strategies, which are mainly relevant to structural building materials, most of the other options are applicable to building services systems directly or in modified form. The scoping interviews conducted as part of this study indicate that the impact of these strategies on building services design would mostly relate to decisions on the level of servicing for a building, the choice and sizing of systems and products to meet a given specification and opportunities to reduce material use by leaner design and product re-use.

2.9 Chapter summary

This chapter began by reviewing the literature informing the background to this study. The case for embodied carbon reduction in the built environment was established and the contribution explained that this could make to the wider aims of meeting GHG emissions targets and addressing resource efficiency and the circular economy. The limitations of these aims were considered as well as the activity outside the scope of this study that would need to accompany embodied carbon estimation within UK construction. It was established that three key topics within the problem space required critical examination in academic and other literature. These were (a) barriers and drivers affecting UK construction industry practice on embodied carbon (EC); (b) calculation methods, data and tools for EC in building services; and (c) decision-making on HVAC system design.

(a) A review of studies of barriers and drivers to carbon reduction in construction showed that various theoretical approaches had been used and that the scope of published findings had not covered the specific issue of embodied carbon in building services. The further investigation of this topic via primary research with stakeholders was shown to have value in informing the development of an embodied carbon estimation method. This supports the following study objective:

RO1 To identify a range of barriers and drivers that inform industry practice on the calculation and reduction of embodied carbon in building services systems.

(b) A review of methods, data and tools used by LCA studies highlighted various methodological challenges intrinsic to the LCA approach and the extent to which these challenges hindered estimation of embodied carbon in building services during early building design, both for components and for building-wide systems. A possible solution using parametric estimation along with statistical analysis of parameter uncertainty was proposed, along with the option of using computationally efficient analytical uncertainty propagation methods rather than sampling-based methods to achieve this. This supports the following study objectives:

RO2 To develop an estimation method for embodied carbon of composite building services components that addresses uncertainty of input parameters.

RO3 To apply the estimation method to the comparison of embodied carbon impacts of alternative building services systems, initially focusing on heating, ventilation and air-conditioning (HVAC) systems.

RO5 To produce a specification for a tool for practitioners to compare HVAC systems using embodied carbon.

(c) A review of academic and other literature on design choice applied to HVAC systems showed that rational choice was often assumed to exist by default. The assumptions central to rational choice theory were examined and compared with a range of other theoretical approaches involving heuristics and/or intuition. It was established that the theory of bounded rationality could help explain decision-making in HVAC design and that as very little published work existed in this area, a case could be made for additional primary research with design teams. This also supports the following study objective:

RO4 To identify and explain the decision-making processes involved in selecting options for the design of HVAC systems for office buildings.

Finally the theoretical challenge posed by the problem space was considered. It was noted that the main theoretical approach underlying the study, LCA, was by nature based on an apparently positivist paradigm and concerned quantitative measurement of environmental impacts. However, the need for LCA studies also to model real world issues was shown to support a reclassification of LCA as informed by post-positivism as well as the inclusion in some LCA studies of other theoretical approaches to model the social domain. This provided support for the use in the present study of the choice theory to consider design decision-making, provided that the research paradigms informing all theoretical approaches used in the study were compatible.

3 Research design

3.1 Introduction

This chapter describes the research design in terms of its philosophical paradigm, approach to theory development, methodological basis, strategies of inquiry, time horizon and individual research methods. The research questions derived from the five research objectives that were first presented in chapter 1 are identified, after which the chosen mixed methods approach is justified and discussed. The strategies of inquiry used to investigate each research objective in chapters 4-7 of this thesis are then discussed and the individual research methods are summarised. While the present chapter provides an overview of the research design, operational details of individual research methods are outlined following the respective introductory sections of chapters 4-7. The approach taken to integration and validation of research findings is then discussed, after which the chapter is summarised.

3.2 Research questions

Figure 3.1 shows the key research questions derived from the core objectives. The questions are interrelated, each building progressively towards understanding the requirements of guidance on the selection of HVAC systems on the basis of their embodied carbon impacts. The relatively broad scope and different types of information needed to address the research questions has implications for the type of research design possible and the detailed research methods to be used, and these will be discussed below.

Research objectives	Research questions
RO1: To identify a range of barriers & drivers that inform industry practice on the calculation and reduction of embodied carbon (EC) in building services systems	**RQ1:** What are the determinants for decisions on whether or not to measure/reduce EC in the design of systems of building services?
RO2: To develop an estimation method for EC of composite building services components that addresses uncertainty of input parameters	**RQ2a**: Can a parametric EC estimation method be developed for generic HVAC components and systems? **RQ2b**: How do uncertainties in input parameters affect EC estimates of HVAC components & systems?
RO3: To apply the estimation method to the comparison of EC impacts of alternative building services systems, initially focusing on HVAC systems	**RQ3.** Can significant differences be measured between EC impacts of alternative HVAC systems?
RO4: To identify and explain the decision making processes involved in selecting options for the design of HVAC systems for office buildings	**RQ4.** How and why are particular design options selected for HVAC systems in office buildings?
RO5: To produce a specification for tool for practitioners to compare HVAC systems using EC	**RQ5.** What are the functional requirements of a guide for practitioners to compare HVAC systems using EC?

Figure 3-1: Research questions derived from study objectives

3.3 Research design - overview

Research design has been described by Creswell as consisting of three components - a philosophical worldview, also known as a research paradigm or knowledge claim, a strategy of inquiry or methodology and a particular choice of individual research methods (Creswell, 2014). A more detailed classification by Saunders, Lewis and Thornhill (2009) describes the components of research design as 'layers' of a 'research onion' of which the philosophical approach is the outermost layer. The layers situated progressively further inwards are respectively the approach to theory development, the methodological choice, the strategy or strategies of inquiry, the time horizon; and the individual research methods used to collect and analyse data. Using this typology, the layers chosen for the research design of this thesis are summarised in Table 3.1 and the reason for their selection is discussed below, while the application of these options to the research objectives and research questions is illustrated in Figure 3.2.

Table 3-1: Summary of research design

Layer of research design	Options used in this study
Philosophical approach	Post-positivism
Approach to theory development	Deduction
Methodological choice	Mixed methods, complex, with sequential explanatory, embedded and concurrent features
Strategies of inquiry employed	Research objective 1: Quantitative survey Research objective 2: Case studies & quantitative analysis Research objective 3: Case studies & quantitative analysis Research objective 4: Qualitative study Research objective 5: Integrated analysis & interpretation
Time horizon	Cross sectional, sequential and concurrent
Individual methods employed	As summarised in Table 3.2

As argued by Small (2011), the terms 'quantitative' and 'qualitative' as applied to the categories in Table 3.1 and Figure 3.1 are best seen as shorthand descriptions of a complex reality, because mixed methods research may involve mixing of a range of data types, data collection methods and techniques of data analysis. In each case, the range of options may not fully be captured by the binary alternatives 'qualitative' and 'quantitative'.

3.3.1 Philosophical approach

The selection of the philosophical layer and other layers of a research design should be informed by the aim or aims and objectives of the investigation and the associated research questions. As shown in Figures 3.1 and 3.2, the aim, four of the five research objectives and five of the six research questions concern the estimation of embodied carbon, a topic that is theoretically rooted in the methods and techniques of environmental life cycle assessment (LCA). This helps identify the appropriate philosophical approach. By and large, LCA studies aim to quantify environmental impacts, using process-based, input-output or hybrid approaches that combine process and hybrid methods for the calculation of these impacts (Chau, Leung and Ng, 2015).

Research objectives	Research questions	Quantitative methods	Qualitative methods	Key outcomes
		Initial literature review		1. Initial research design, 2. Initial LCA goal & scope to inform **RO1**
RO1: To identify a range of barriers and drivers that inform industry practice on the calculation and reduction of embodied carbon (EC) in building services systems	**RQ1:** What are the determinants for decisions on whether or not to measure/reduce EC in the design of systems of building services?	Scoping interviews Online survey of industry stakeholders, mainly quantitative analysis		1. Barriers & drivers identified as per **RO1** 2. Goal & scope of LCA refined to inform **RO2** 3. Identification of topics for further study via qualitative insight in **RO4** 4. Initial user requirements to inform **RO5**
RO2: To develop an estimation method for EC of composite building services components that addresses uncertainty of input parameters	**RQ2a**: Can a parametric estimation method be developed for generic HVAC components and systems? **RQ2b**: How do uncertainties in input parameters affect EC estimates of HVAC components & systems?	Case studies of HVAC components and systems using: (a) Environmental life cycle assessment (b) Analytical and sampling based uncertainty		Pilot EC estimation method incorporating uncertainty analysis developed as per **RO2** to inform **RO3** and **RO5**
RO3: To apply the estimation method to the comparison of EC impacts of alternative HVAC systems	**RQ3.** Can significant differences be measured between EC impacts of alternative HVAC systems?	Further analysis using LCA and uncertainty propagation		1. Method applied as per **RO3** and used to inform **RO5**
RO4: To identify and explain the decision making processes involved in selecting options for the design of HVAC systems for office buildings	**RQ4.** How and why are particular design options selected for HVAC systems in office buildings?		Qualitative survey of mechanical services engineers, thematic analysis of results	1. Choice theory-based insight into decision-making developed as per **RO4,** also informing **RO5** 2. HVAC system types and user requirements clarified to inform **RO3** and **RO5**
RO5: To produce a specification for a tool for practitioners to compare HVAC systems using EC	**RQ5.** What are the functional requirements of a tool for practitioners to compare HVAC systems using EC?	Business requirements analysis, interpretation of findings of previous stages with integration of qualitative and quantitative results		Specification for selection tool developed as per **RO5**

Figure 3-2: Application of mixed methods research design

The process approach measures physical quantities such as mass, energy and emissions to air, water and land. The input-output approach measures economic impacts of industrial sectors on physical quantities of environmental resources at a regional or national level. In both cases, the science needed to measure the physical quantities belongs to a 'post-positivist' paradigm in the sense that it is 'based on a deterministic philosophy in which causes (probably) determine outcomes' and it relies on the scientific method (Creswell, 2014, p7).

The LCA approach, however, attempts to address problems that span the technical and social domain (Heiskanen, 2002) and therefore requires subjective value judgements on the assumptions, boundaries and methods used to describe real world problems. In other words, value judgements are needed because these real world problems are 'messy' in the sense that they are 'ill-defined, surround controversial subjects and involve multiple and conflicting stakeholders perspectives' (Lazarevic et al, 2012, p201). One of the outcomes of this is that LCA studies may include assumptions with theoretical implications about the social domain that can be challenged. For instance, LCA studies have been described as based 'consciously or unconsciously' on a rational theory of policy-making which assumes that society is in agreement on the goals, means and end of a particular LCA study, although this is not always the case in practice (Bras-Klapwijk, 1998, p335). It could be argued, therefore, that in order to have practical relevance, LCA studies need a credible, evidence-based connection with the social context in which they are used, especially if they are intended to inform industry practice, as is the case in this research undertaken as part of an Engineering Doctorate programme.

And while, in these terms, the objectives and questions addressed by this study are also informed by the world of practice-based LCA, they address both *how* embodied carbon can be understood, measured and/or reduced, and also *why* and in what circumstances stakeholders might choose such approaches when designing building services systems. As such the research does not exclusively privilege the more rational, scientific basis of LCA any more than a more socially-informed mode of enquiry that may help understand design decision-making. It is therefore intended to add a practice-based dimension but without requiring the position to be taken that that a philosophy of 'pragmatism' necessarily must inform this type of mixed methods research, as proposed by Johnson and Onwuegbuzie (2004).

Given the challenges inherent in using the LCA approach to describe the social domain that forms part of its background context, LCA researchers have employed theories from outside the physical sciences associated with environmental measurement to assess these social aspects. Examples include the use of game theory (Soltani, Sadiq and Hewage, 2017) and discourse theory (Bras-Klapwijk, 1998) to model stakeholder behaviour. This precedent supports the use of choice theory to investigate decision-making by stakeholders about the design of building services in the present study, which is primarily concerned with the embodied carbon impacts of building services. However if multiple areas of theory are used in a single research study, the philosophical paradigms informing those theories should also be compatible to avoid the threat to validity posed by 'paradigm-mixing' (Onwuegbuzie and Johnson, 2006). In this study, this is enabled by ensuring that the dominant philosophical approach of post-positivism also informs the handling of qualitative aspects of other layers of the research design, which are discussed in the next section.

3.3.2 Approach to theory development

The approach to theory development used in this thesis is necessarily deductive in that data is used to test existing theory, based (a) on environmental life cycle assessment and uncertainty propagation and (b) on rational choice and bounded rationality. It is posited that the use of an inductive approach would not have been suitable, as new theory is not being generated. An abductive approach that uses a theoretical perspective based on the world-view of the research participants (Bryman, 2012) could have been used to inform the study of design decision-making for research objective 4, however the richness of existing choice theory identified earlier in the literature review offers ample opportunity instead for the use of a deductive approach to examine existing theory.

3.3.3 Methodological choice

The methodological approach chosen for the research comprises a mixed methods research (MMR) design. The justification for this is firstly that a solely quantitative or qualitative approach would be unable adequately to address the scope of the research questions. As shown in Figure 3.2, research questions RQ1-RQ5 explore not only issues around estimation and measurement of embodied carbon but also issues around how and why stakeholders make particular choices in building design. However, the ability of MMR methodology to accord unequal weight between quantitative and qualitative aspects (Creswell and Plano Clark, 2011) suits a study in which the main topic in focus is investigated by a quantitative estimation method.

Secondly, there are five widely cited reasons for choosing MMR designs according to Greene et al (1989), which are triangulation, complementarity, initiation, development and expansion. Four of these are supported by the proposed research design, as will be discussed below. Thirdly, the research design used draws on three of the four main types of MMR designs found in research literature, which are concurrent, embedded, sequential exploratory and sequential explanatory (Creswell and Plano Clark, 2011).

Such a hybrid design can be classified as 'complex'. It offers a more creative, dynamic way to address the research aim than might be possible with a 'typological/taxonomic' approach in which the inquiry is moulded to fit a pre-defined design (Johnson And Onwuegbuzie, 2004, Schoonenboom and Johnson, 2017). In Figure 3.2, the use of a sequential explanatory design means that a survey-based, mainly quantitative phase of data collection and analysis for RO1 is followed by a qualitative study for RO4, in order to gain deeper insight into the survey results. RO4 also uses an embedded design to add options for textual comments into a mainly quantitative survey questionnaire. While the five research objectives are implemented sequentially, a concurrent approach is used where necessary within one research objective to collect multiple data types and/or employ multiple methods of data collection. A concurrent approach also describes the data analysis for research objective RO5, where multiple data types from preceding stages of the inquiry are integrated.

The research design is intended to support complementarity between methods in that research objectives RO1-RO4 use primary research to measure 'overlapping but different facets of a phenomenon', (Greene, Caracelli and Graham, 1989, p258) rather than attempting to triangulate by using multiple methods to measure exactly the same subject. The research design also supports development in that the strategy used to investigate each research question is informed by the results of investigations of previous research questions. Lastly the research design supports expansion of the scope of the study by using different strategies to investigate different research objectives.

3.3.4 Strategies of inquiry employed

As shown in Figure 3.2, the strategies used to collect and analyse primary data for research objectives 1, 2 and 4 are respectively an online survey of stakeholders, a series of case studies of HVAC components and systems and a qualitative study of stakeholders. Research objectives 2, 3 and 5 focus on data analysis and use strategies for the analysis and use of EC data accordingly. These are the use of LCA methodology and uncertainty analysis for RO2 and RO3 and business requirements analysis for research objective RO5. While the strategies used differ in content, they are necessary ingredients of a joined-up process to achieve all five research objectives, as shown by the 'key outcomes' column in Figure 3.2. Each of these strategies is now discussed.

3.3.4.1 Research objective 1: To identify a range of barriers and drivers that inform industry practice on the calculation and reduction of embodied carbon of building services systems.

A survey of UK-based construction industry professionals is used to investigate RO1. The sampling strategy used ensures that a broad range of occupations are represented in order to obtain a rounded perspective on the subject matter and that the sample size is sufficient to support statistical analysis of variation between responses by sub-group. The survey uses mainly closed questions combined with options for further comments in some areas. This provides an evidence base to refine the goal and scope of the LCA study on embodied carbon and prepares the way for the investigation of RO2. Secondly, by investigating stakeholder perceptions on various topics associated with resource efficiency, building services and embodied carbon, the survey allows selection of specific areas of relevance to be explored qualitatively in the study of design decision-making for RO3. Thirdly, the survey provides initial indications of views of construction industry professionals on the feasibility and user requirements of a selection guide applicable to building services based on their embodied carbon impacts, to inform RO5.

3.3.4.2 Research objective 2: To develop an estimation method for embodied carbon of building services that addresses uncertainty of input parameters; and research objective 3: To apply the estimation method to the comparison of embodied carbon impacts of alternative building services systems, initially focusing on HVAC systems.

To investigate RO2, a process-based, attributional LCA study of product-stage embodied carbon (EC) is used for a series of case studies of heating, ventilation and air-conditioning (HVAC) components, the first three of which focus on comparative EC impacts of fan coil units made by UK based manufacturers. To investigate RO3, the method is further developed using a case study of the main components making up four installed HVAC systems, which belong to three generically distinct types and are summarised in Table 3.2.

Table 3-2: Components investigated in case studies

	Building number and HVAC system type *(FCU=fan coil unit, VRF= variable refrigerant volume, VAV= variable air volume)*			
Component details	**1 - FCU**	**2 - VRF**	**3 - VRF**	**4 - VAV**
Air-cooled chiller with screw compressor, 400kW capacity x 2 No	X			
Air-cooled centrifugal chiller, 7,759 kW capacity				X
Air handling units - various sizes, various materials	X	X	X	X
Attenuators - galvanised sheet steel	X			X
Condenser boiler, 750 kW	X			
Ductwork - galvanised sheet steel	X	X	X	X
Fan coil units (FCUs), various sizes and raw materials	X			
Linear air diffusers - aluminium	X			
Pipework - carbon steel, used for low temp hot water/chilled water	X			
Pipework - copper - tube and sheet, used for low temp hot water/chilled water, refrigerant		X	X	X
Swirl air diffusers, aluminium and plastic		X		
Fan assisted variable air volume (VAV) terminal unit, various materials and sizes				X
Variable refrigerant volume (VRF) indoor terminal unit, various materials and sizes		X	X	
Variable refrigerant volume (VRF) rooftop condenser unit, various materials and sizes		X	X	

A case study strategy is chosen because while case studies have been traditionally associated with qualitative techniques used in the social sciences, they can also 'include, and even be limited to, quantitative evidence' (Yin, 2014, p19). Case studies investigate contemporary phenomena 'in depth and within a real world context' and rely on 'multiple sources of evidence, with data needing to converge in a triangulating fashion' (Yin, 2014, p16-17). A recent review of published LCA studies in construction confirm the use of case studies that include quantitative evidence to investigate real world problems (Cabeza et al, 2014), although it shows that published LCA 'case studies' may refer to notional or modeled buildings as well as real buildings as designed or as constructed, therefore the real world context is not always present in these studies. However as argued earlier, LCA studies need a credible interface with their real world context, so the case studies used in this thesis are of installed building services systems.

The reasons for choosing HVAC systems in office buildings as case studies are as follows:

- *Choice of the office sector:* The UK office sector is the second largest category by value of commercial property after retail (Property Industry Alliance, 2017) and provides the second largest category by value of 'new work' in mechanical and electrical building services, after housing (BSRIA, 2017).
- *Choice of HVAC systems and components:* A empirical study by the project sponsor of embodied carbon (EC) in 30 new office buildings (AECOM, 2012) indicates that HVAC systems, defined by the combined cost categories of 'heat source', 'space heating and air treatment' and 'ventilating system', are responsible for on average 75% of product stage EC of all building services systems.

The outcome of the investigation into RO2 and RO3, as shown in Figure 3.2, is a method to estimate embodied carbon for generic building services components and systems. This in turn informs the investigation of RO4 and RO5, in which the estimation method is further analysed and implemented in a specification and pilot application of an HVAC system selection tool.

The second aspect of the investigation of RO2 is the investigation of parameter uncertainty. The life cycle inventory analysis and impact assessment undertaken for the case studies listed in Table 3.2 can provide deterministic estimates of embodied carbon (EC) values, but as the number of case studies is limited, a way is needed to quantify the uncertainty of these estimates if applied to other components and systems of the same generic type. An uncertainty analysis of input parameters will enable decisions to be made on whether the difference between estimated embodied carbon values of two alternative components or systems is statistically significant, given what is known about the uncertainty of each estimate.

Given the research problem addressed by this study as described in section 1.2, the issue to be investigated here is parameter uncertainty of the values for material type, mass and carbon intensity during the product stage of life of HVAC systems and their constituent components. While two potential strategies of uncertainty reduction and uncertainty incorporation were discussed in section 2.6.1, the use of uncertainty reduction alone would be insufficient in this case for three reasons. Firstly, the 'scientific' approach of collecting enough data to measure all necessary input parameters empirically would not be practicable as the practical challenge addressed by this study is to devise an estimation method for a type of product system in which some input data will always be unknown or uncertain. Secondly, the 'constructivist' approach of expert elicitation would be unlikely to provide the kind of missing quantitative data required, given uncertainty about the type and quantity of individual raw materials used in composite HVAC components and systems. A recent study has used expert elicitation to quantify and thereby reduce input parameter uncertainty of embodied carbon coefficients for simple building materials such as steel and timber used in supermarket construction (Richardson, 2017). However, input parameters for material quantities were treated as deterministic variables extracted from BIM models rather than sources of uncertainty, an approach which would not be suitable for a study of HVAC systems. Thirdly, the 'legal' approach to uncertainty reduction via LCA standards offers processes for calculation of input values, but not a source of missing input values. It is therefore necessary to consider how parameter uncertainty might be included in the analysis using a suitable method of uncertainty propagation.

Following from the discussion in section 2.6.3 in which sampling based and analytical methods of uncertainty propagation were compared, there are three factors that support the use of first-order analytical uncertainty propagation (AUP) in embodied carbon estimation in the present study. Firstly, while AUP does not estimate an output probability distribution, it can support a comparison between embodied carbon estimates of products based on variance. Because AUP assumes that uncertain input parameters have a normal (Gaussian) probability distribution, confidence intervals can be estimated for the output value (Heijungs and Lenzen, 2014). If the distribution is normal in practice, the confidence interval obtained by AUP will not differ significantly from that obtained by MCS. Using AUP, a 95.5% confidence interval corresponding to a distance of plus or minus twice the standard deviation of a normal distribution can then be used to measure whether the difference between output uncertainty of two embodied carbon estimates is significant. Secondly, the accuracy of AUP against Monte Carlo simulation (MCS) can be tested, as will be done in the present study. Thirdly, covariance between uncertain inputs tends to be excluded from scope of sampling-based uncertainty propagation in LCA, because its sources are usually unknown (Heijungs and Lenzen, 2014). Moreover, a recent study has demonstrated the applicability of AUP to estimating the uncertainty of variations in mass, embodied impacts and service life of building components in residential housing (Hoxha et al, 2014). The present study could therefore adapt this approach to the specific challenge of uncertainty around the mass and environmental impact of raw materials included within composite building services components. This would have two advantages - computational simplicity compared to a sampling-based method and the ability to improve on deterministic estimation of uncertain input parameters.

How else might parameter uncertainty be addressed in estimation of embodied carbon of building services? In one sense a focus on building services systems and components that fall into demonstrably generic types can reduce parameter uncertainty by establishing categories of material type and ranges of mass values associated with a type of component or system of components. This is analogous to the approach used in sizing building services components with 'rules of thumb' (BSRIA, 2011) and would be relevant in developing a parametric approach to estimating embodied carbon impacts of HVAC systems. However, to avoid inaccurate deterministic estimation where gaps exist in input data, parameter uncertainty should also be addressed via statistical methods of uncertainty analysis. In doing this, AUP is potentially more suitable than sampling based methods such as for rapid estimation of EC during early building design because of its computational simplicity, provided that the necessary qualifying assumptions on covariance and input uncertainty are met for its use (Heijungs and Lenzen, 2014).

The rationale for testing alternative methods of uncertainty propagation in an LCA based case study of buildings or building components was outlined in section 2.6.3. Based on established methods, the test can be implemented using five steps, which are a contribution or gravity analysis, a sensitivity analysis, an uncertainty analysis, an uncertainty contribution analysis and a discernibility analysis (Heijungs and Kleijn, 2001, Bjorklund, 2002, Clavreul et al, 2012). The parameters being tested here are mass, raw material type and EC intensity for the product stage of each raw material, but the methods used are equally applicable to other parameters that affect recurring EC such as component service life and number of replacement cycles.

The contribution or gravity analysis is used to identify parameters by their relative contribution to part or all of the life cycle inventory impacts (Heijungs and Kleijn, 1996, BSI, 2006b). This enables exclusion of any parameters whose relative contribution is likely to be small in relation to total EC impact after sensitivity and uncertainty analysis. After this, a sensitivity or perturbation analysis is used to vary selected input parameters by small amounts to measure the effect on EC output. Having identified the most sensitive input parameters, the likely range of variation for the most sensitive parameters can be found. To conduct the uncertainty analysis, which is defined as the 'systematic study of propagation of input uncertainties into output uncertainties' (Heijungs and Kleijn, 2001), we require for each input parameter a nominal value, an upper and lower range, an assumed probability distribution and a variance value. These values are used to test the method of first-order analytical uncertainty propagation (AUP) against the sampling-based alternative, Monte Carlo Simulation. After this, an uncertainty contribution analysis, also known as uncertainty importance analysis, calculates the contribution to variance of the embodied carbon output value made by the variance of each input parameter (Bjorklund, 2002). Finally, a discernibility analysis is used to compare whether the difference between the calculated mean embodied carbon impacts of two alternative HVAC components or systems is large enough to make the differences between the mean values of the two impacts insignificant (Heijungs and Kleijn, 2001).

3.3.4.3 Research objective 4: To identify and explain the decision-making processes involved in selecting options for the design of HVAC systems for office buildings

A qualitative study using semi-structured interviews with mechanical building services engineers (MSEs) is used to investigate RO4. In accordance with the sequential explanatory approach to MMR, this is done to provide further insight into selected issues previously identified by the stakeholder survey. The decision to limit the scope of the sample frame to MSEs is also informed by the survey results, which identify this role as one with the most influence on the design of HVAC systems in office buildings. Other aims of the qualitative study are to clarify the physical system boundary of an 'HVAC system' used for the embodied carbon analysis of HVAC systems addressed by research objective RO5 and to examine how and why HVAC systems are chosen by design teams in relation to the explanations proposed by various choice and decision-making theories. The results are then coded and analysed using thematic analysis (Ryan and Bernard, 2003). This informs the development of the comparison between HVAC systems in RO3 and ensures that specification for the embodied carbon estimation tool developed for RO5 has a real world evidence base and practical applicability.

The known challenges of using a qualitative method within a predominantly quantitative research study include the practical issue of ensuring that available resources and skills allow both elements to be implemented and integrated appropriately (Johnson and Onwuegbuzie, 2004) and the theoretical issue of commensurability, in that qualitative and quantitative methods reflect different epistemologies 'which by definition hold different assumptions about the nature of truth' (Small, 2011). To minimise this challenge, the research techniques chosen should not be too closely tied to incompatible epistemological positions, as might be the case if a decision to purchase clothes was analysed by combining the methods of neoclassical economics and ethnomethodology (Small, 2011). This risk is minimised by combining survey and interview data in what is considered the most common mixed method design (Fielding, 2012), a combination with a track record in supporting commensurability.

3.3.4.4 Research objective 5: To produce a specification for a tool for practitioners to compare HVAC systems using embodied carbon

RO5 brings together the results of the four previous research objectives primarily to inform the specification and pilot implementation of an embodied carbon selection tool for HVAC systems. The methodological framework used to do so is business requirements analysis (Paul et al, 2014), a systematic approach designed to transform social and technical information into a high-level specification of business needs which can be used as the basis for a software specification. This contributes to the mixed methods research design by providing concurrent integration of data of different types obtained from investigating the first four research objectives. It also supports complementarity between research methods, in that the qualitative study informs the choice mechanism and accessibility of the tool while the embodied carbon and uncertainty analysis informs its numerical inputs and outputs. The analysis carried out for RO5 also feeds into a general discussion chapter in which the background literature, research objectives and planned theoretical contributions are reviewed in the light of the overall research findings.

3.3.5 Time horizon

The time horizon layer of research design as used by Saunders, Lewis and Thornhill (2009) concerns whether the study is cross-sectional or longitudinal, although these two options do not fully capture the time dimension of a mixed methods research design. In this research, the survey used to address RO1 is cross-sectional and the relationship between research objectives RO1-RO5 is primarily sequential without forming part of a longitudinal study. For a more nuanced classification, Schoonenboom and Johnson (2017) regard timing as one of the primary dimensions of a mixed methods research design and divide it into two aspects, simultaneity and dependence. Simultaneity refers to whether data in different components of the research takes is collected concurrently, sequentially or using a multiphase design, combining both methods. Dependence refers to whether the data analysis in a later component of the research depends on the analysis of an earlier component (Schoonenboom and Johnson, 2017). This distinction is useful as it allows for the possibility that not all sequential designs are dependent and not all concurrent designs are independent.

In this research, the position on simultaneity is that each of the research objectives can be considered a distinct phase of a multiphase study. Data collection happens sequentially from RO1 through to RO3, but concurrently where different types of data are collected or analysed for the same research objective. The approach to dependence in this thesis is selective in that phases RO2-RO5 depend on the analysis of some, but not all, previous phases. As shown in Figure 3.2; RO2 depends on RO1 to clarify the goal and scope of the LCA, RO3 depends on extending the results of RO2; RO4 depends on RO1 to support selection of topics and participants for more in-depth study; and RO5 depends on all four previous research objectives.

3.4 Integration

Integration has been described as being 'at the heart of' mixed methods research because the purpose of MMR is to bring together, or mix, information from multiple sources (Fielding, 2012). Integration may entail mixing types of data, data collection methods and/or methods of data analysis (Small, 2011). Possible ways to achieve integration include established design options for the overall research study such as the main sequential and concurrent variants as well as bespoke options developed to meet the needs of individual studies. The way in which integration is achieved should reflect the purpose for which a mixed methods was chosen (Greene et al, 1989) as well as being able to stand up to the particular threats to validity presented by such a mixed design (Fielding, 2012). In this research, the use of integration reflects the purposes of complementarity, development and expansion. The survey used for RO1 is a single data collection method that integrates two complementary data types using an embedded design. The analysis of the survey that addresses RO1 integrates these two data types by using qualitative comments to expand understanding of quantitative results of particular questions. The development of the estimation method to address RO3 and RO4 integrates the collection of quantitative data on parameter values with complementary normative data on the definition and boundaries of the product systems being studied. The qualitative study used for RO4 develops and expands on the analysis of the survey findings from RO1, thus integrating two phases of the study, one mainly quantitative and one mainly qualitative, via a sequential explanatory link between phases. The specification that is the subject of RO5 integrates the quantitative embodied carbon estimation method with complementary qualitative data about user needs from the survey and qualitative study.

3.5 Methods used for data collection and analysis

Table 3.3 summarises the methods used for each of the five research objectives to collect and analyse data, as well as the data types that are used, defined by source. Further details of individual methods employed in each phase of the study are outlined in the 'methodology' sections of chapters 4-7.

Table 3-3: Data types and methods of data collection and analysis

Research objective	Method of data collection	Type of data by source	Method of data analysis	Tools used for analysis
RO1: To identify a range of barriers and drivers that inform industry practice on the calculation of embodied carbon (EC) of building services	Web-based survey of UK construction industry professionals	Quantitative data from Likert scale questions Qualitative comments from questionnaires	Statistical and descriptive analysis	'Smartsurvey' online survey creation tool (Smartsurvey Ltd, 2018) MS Excel 'R' statistical package
RO2: To develop an estimation method for EC of composite building services components, that addresses uncertainty of input parameters **RO3:** To apply the estimation method to the comparison of EC impacts of alternative building services systems, initially focusing on HVAC systems	Desk research Quantity take-off from design drawings and BOM models Field experiments on construction sites using 'tear down' analysis	Design drawings BIM models Manufacturers' bills of materials LCI databases DEFRA and DECC emission factors Environmental product declarations Published LCA studies Experimental measurements	LCA methods as per ISO standards (BSI, 2006, 2011, 2014) Analytical and sampling-based uncertainty propagation	MS Excel Simapro 8 LCA software (Simapro UK, 2018) and Ecoinvent v.3.1 (Ecoinvent, 2014) E-tool LCD LCA software (Etool, 2018) ICE LCI database (Hammond and Jones, 2011)
RO4: To identify and explain the decision-making processes involved in selecting options for the design of HVAC systems for office buildings	Qualitative study of mechanical building services engineers	Interview transcription	Coding and thematic analysis	VBA macros in MS Word MS Excel
RO5: To produce a specification for a tool for practitioners to compare HVAC systems using EC	Further analysis of data collected in previous phases	Uses data from previous 4 Research objectives	Business analysis of technical and user requirements	MS Excel

3.6 Validity and threats to validity

Validity concerns the extent to which a research study and its constituent parts can be deemed to be 'of high or low quality or somewhere in between' (Onwuegbuzie and Johnson, 2006). In mixed methods research this is a contentious area, because while there is a history of definitions of validity in quantitative research, qualitative researchers have considered validity to be a concept that is ‘unclear and ambiguous’ (Dellinger and Leech, 2007). Table 3.4 provides a summary of the definitions to validity used in this thesis for the various research objectives, typical threats to validity and ways in which these threats are mitigated. The first two rows of Table 3.4 present the strategy used for those Research Objectives that are investigated with a mainly quantitative or qualitative strategy. In these cases ‘standard’ approaches to define validity, threats to validity and ways to mitigate those threats are used. In the third row, Onwuegbuzie and Johnson’s concept of ‘legitimation’ (2006) is used to define and address threats to validity specific to the integrated areas of the thesis.

An important feature highlighted by Table 3.4 is that most LCA studies address quantitative threats to validity, especially internal validity, with the support of existing LCA quality standards, so their approach to validity reflects the first row of the table. Few LCA studies however take the position that the intrinsically mixed data and data collection methods needed for an LCA study might necessitate a focus on threats to validity specific to mixed methods research. As LCA combines a rational approach to quantification with normative framing to define what should be measured and how it should be measured (Bras-Klapwijk, 1998), it may face the threat of ‘paradigm mixing’ (Onwuegbuzie and Johnson, 2006). This can be mitigated by treating the methods and assumptions associated with each paradigm as separate but complementary.

Table 3-4: Mitigation of threats to validity

Methodological choice	Where applicable in thesis	Type of validity or legitimation	Examples of threats to validity affecting research design, data collection, analysis or interpretation	Examples of mitigation of threats to validity in this thesis
Quantitative	Research methods used for research objectives RO1, RO2 and RO3	Internal validity - (a.k.a. construct or measurement validity) External validity Reliability (Bryman, 2012, Yin, 2014)	*Internal:* Model not appropriate to measure variable *External:* Sample not large or representative enough of population *Reliability:* Measurement method not consistent or replicable elsewhere	*Internal:* Alignment of embodied carbon estimation model used in RO2 with ISO LCA quality standards (BSI, 2006, 2011, 2014) *External:* Ensuring that online survey used in RO1 is marketed across construction industry and responses meet appropriate target level *Reliability:* Ensuring that method used in RO3 to compare EC of HVAC systems is potentially applicable to other components and systems
Qualitative	Research method used for Objective RO4	Credibility (a.k.a. contextual validity) Transferability Dependability (Lincoln and Guba, 1985)	*Credibility:* Observer-caused effects and researcher bias in data collection *Transferability:* Failure to compare empirical findings with previous cases and theories *Dependability:* Errors in data classification	*Credibility:* Interview protocol and question design for qualitative study used in RO4 minimises observer effects and bias. Findings also used to complement survey results. *Transferability:* Findings of qualitative study done for RO4 are compared with theories of rational choice/bounded rationality and related studies *Dependability:* Data analysis used in RO3 relies on established techniques of thematic analysis
Mixed	Integration between RO1-3 and RO4 Integration used for data analysis in RO5 and thesis discussion / conclusions	*Types of legitimation:* -Sample integration -Inside out -Weakness minimisation -Sequential -Conversion -Paradigm mixing -Commensurability -Multiple validities -Political (Onwuegbuzie and Johnson, 2006)	*Sample integration:* The more that qualitative and quantitative samples differ in type or size, the less reliably can meta-inferences be drawn from both *Conversion:* Inherent challenges in drawing meta-inferences from quantitative data converted into qualitative data or vice versa *Paradigm mixing:* Risk of assumptions on research paradigm not being made explicit and research not being conducted according to these assumptions	*Sample integration:* While qualitative sample used in RO4 is partly a subset of quantitative sample from RO1, it is used to complement and not triangulate the first sample, so it considers overlapping rather than identical subjects *Conversion:* Threat mitigated by leaving qualitative and quantitative data in their original format rather than attempting to convert *Paradigm mixing:* Threat mitigated by ensuring that qualitative and quantitative approaches are treated as separate but complementary rather than as a continuum

3.7 Chapter summary

This chapter has outlined a layered approach to research design adopted for the thesis. The broad nature of the research questions has been shown to inform the choice of a complex, mixed methods research design with sequential, concurrent and nested features, located in a post-positivist research paradigm and with a deductive approach to theory development. A five-stage strategy of inquiry was outlined, with a different strategy used to address each of the five research objectives. The approach to timing, integration and threats to validity was then discussed and the strengths and weaknesses of the position taken in each case were discussed.

4 Survey results on resource efficiency in building services design

4.1 Introduction and objectives

This chapter addresses the first research objective, RO1, by investigating practical barriers and opportunities related to the measurement and reduction of embodied carbon (EC) in building services systems and components, using a survey of UK construction industry practitioners. In so doing it also addresses the first research question by asking what factors might influence decisions about EC measurement or reduction by practitioners. While the primary focus is on EC of building services, the survey questions also consider the perceived significance of EC in relation to other environmental impacts and associated intervention strategies associated with resource efficiency in the built environment. The survey also supports three other research objectives, as shown in the schematic in Figure 3.2. Firstly, it helps refine the goal and scope of the life cycle assessment (LCA) used to address research objectives 2 and 3. Secondly, it identifies topics and survey respondents for further investigation by the qualitative study associated with research objective 4. Thirdly, it provides initial data on user requirements to inform the specification for an associated with research objective 5. Besides this, the survey also presents a self-contained picture of the way that a range of environmental impacts of building services systems are perceived by those who design and oversee the installation of those systems, including but not limited to the operational energy and carbon impacts most targeted by policy and market requirements The remaining sections of this chapter comprise a summary of the methodology used for survey design, data collection and analysis; the main survey findings; a discussion on the significance of these findings and related limitations; and some initial conclusions from the analysis.

4.2 Methodology

As indicated in the previous chapter, the approach to data collection and survey design for this research is informed by a mixed methods research design in that it uses embedded and sequential methods of integration. The survey collects mainly quantitative data from closed questions, supplemented by qualitative comments fields allowing expansion and explanation or response to key questions. This embedded approach to integration of different data types in turn helps to identify a selection of topics for further investigation by a separate qualitative study that follows as part of a sequential explanatory research design.

The sampling strategy for this survey aimed firstly to select industry practitioners from a range of professional roles, including those involved in some way with building services but not limited to building services designers; and secondly to achieve a sample size that might be sufficiently representative of this target group. The aim was to use views of practitioners from multiple disciplines on issues around building services and resource efficiency to complement the perspective of building services designers, who were likely to have most technical insight into their discipline but might only represent a single professional perspective. This would enable similarities and differences to be identified between views of building services designers and others on key topics.

A web-based, self-completion questionnaire rather than a postal survey or individual interviews was chosen because of the advantages offered by this method. These include comparative speed and low cost in achieving a given sample size, the ability to target a specific professional audience via online networks, the avoidance of bias from 'interviewer effects' and the ability to prevent the questionnaire being read as a whole before each individual question is answered (Bryman, 2012). Key disadvantages of this type of questionnaire compared to postal surveys may include lower response rates, exclusion of respondents without online access and the risk of multiple replies from the same respondent (Bryman, 2012). These drawbacks were respectively mitigated (a) by circulating a link to the survey via online professional networks with a combined circulation of over 1,000 individuals; (b) by the choice of a professional target group for whom online access is routine; and (c) by the automated tagging of each completed questionnaire with a unique code linked to a respondent's IP address to identify duplicate replies. The specific networks targeted with an invitation to complete the survey included the following:

- The UK internal email directory of the project sponsor, a multi-disciplinary AEC consultancy (circulation of over 1000);
- The general and 'Young Engineers' Group' LinkedIn networks of CIBSE (combined circulation of over 10,000). These networks were chosen as a way to maximise access to UK-based building services engineers, as CIBSE is the main trade body covering a cross section of building services disciplines;
- Bespoke lists of construction clients of the project sponsor and of building services product manufacturers contacted during the research project to request product information (around 50 in total).

The questionnaire, a copy of which is attached at Appendix 3, was designed in four sub sections. These consisted of an introduction explaining the purpose of the survey, a section seeking demographic information about respondents, a section seeking general views about resource efficiency and a section seeking views on specific interventions to measure environmental resource impacts. The questionnaire was designed to be completed within 10 minutes and included 11 closed questions, of which six used a Likert scale for multiple indicator measures. A comments field was added to four questions to allow respondents to explain their response choice in more detail. Of the six Likert questions, three used a five-point scale with one middle category for 'neither' of the opposing sets of categories while the other three included two middle categories of 'neither' and 'don't know'. This approach was used only in questions where some of the response options were considered likely to be unfamiliar to a general construction audience.

The survey was implemented using an online survey creation tool (Smartsurvey, 2018) over a two month period between October and December 2014. A total of

130 responses were received, of which 60 were partially completed, leaving 70 fully completed questionnaires. The data from closed questions was then analysed using Microsoft Excel and the statistical package 'R', with qualitative comments analysed within a thematic analytical structure. The statistical test used to identify whether differences in responses to Likert questions by sub-groups were statistically significant was the Mann-Whitney test, also known as the Wilcoxon Rank Sum test (Corder and Foreman, 2014). This is the preferred, non-parametric testing method for ordinal data, enabling a null hypothesis that two independent samples are drawn from the same parent population distribution to be tested against an alternative hypothesis that they are not, to a given confidence level. The test is also adjustable for the effects of small sample sizes (under 20). For this study, the parent population was all 70 of the survey respondents and the confidence level used was 95%. The pairs of sub-groups tested were (a) respondents working for the project sponsor against those from other organisations; (b) building services designers against non-designers; and (c) respondents divided by each of four sub-group representing years of service (<10, 10-19, 20-29, 30+) against the remainder of the sample.

4.3 Characteristics of the sample

Out of the 70 completed questionnaires, 54 (77%) were from respondents employed by the project sponsor (AECOM) – a multi-disciplinary global consultancy working in the built environment, while 16 or 23% were employed by a range of other organisations,. While this pattern of responses does not fully reflect the potential population of practitioners working with building services available via online professional networks, it suggests that internal marketing by the project sponsor was relatively more effective because respondents were aware that the research project had the support of their employer. The risk of any bias in survey responses associated with some respondents having the same employer was addressed via statistical testing for each question, as outlined in the previous section.

In terms of respondents'' construction experience, the mean number of years in the industry was 15 and the median was 10, indicating a distribution skewed towards the lower end of the length of time served, as shown in Figure 4.1. A total of 64% of the overall sample of survey respondents had been in the industry for 15 years or less.

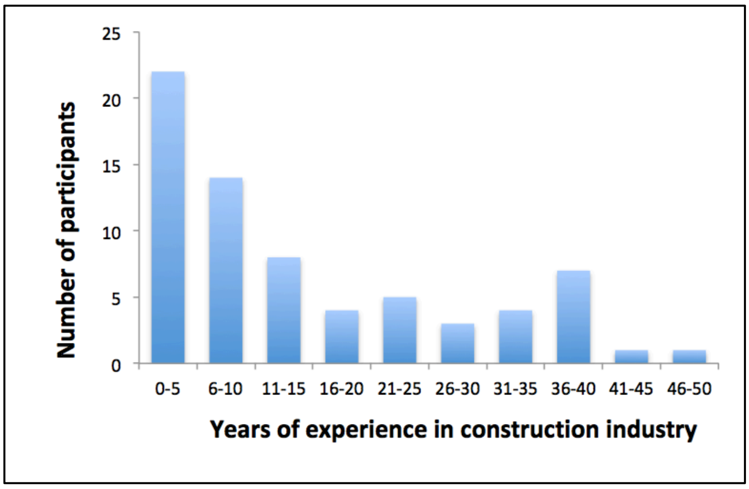

Figure 4-1: Survey respondents by years of experience in construction

A question on job roles asked respondents to select any number of 10 preset categories along with an 'other' category with a comments field attached to describe their main area(s) of work. In response, Figure 4.2 shows that a majority (71%) describe their work as designing and/or specifying building services. Specifically, 69% of respondents design building services, of whom 71% also specify building services, while 51% of respondents specify building services, of whom 97% also design building services. For convenience, the term 'designer' will be used hereafter to refer to both of these sub-groups. Of those not involved in designing or specifying building services, the most common job roles were sustainability assessment within the 'other' category, selected by 10% of respondents followed by research selected by 7%.

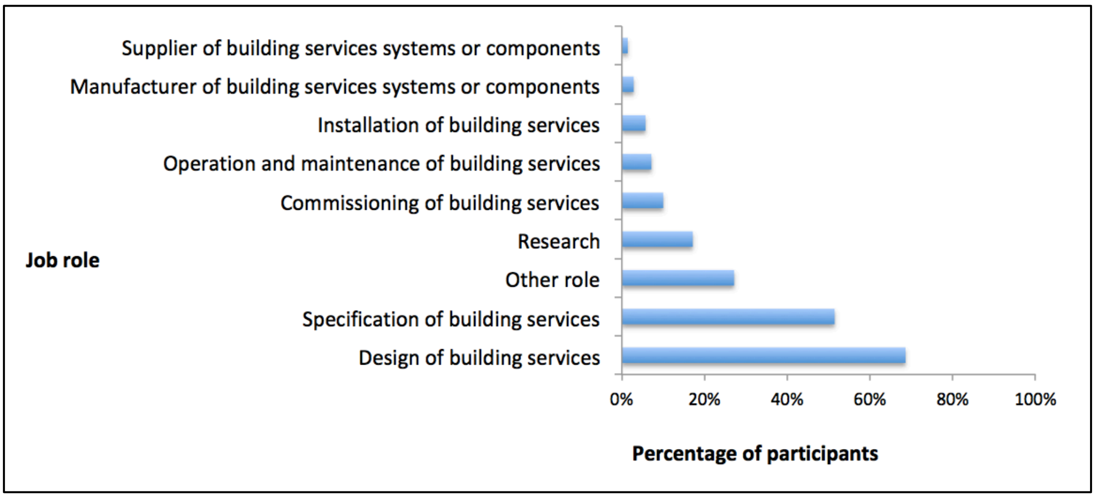

Figure 4-2: Survey respondents by main job role

4.4 Main findings

4.4.1 General perception of resource efficiency

Respondents were asked whether they believed that 'building services systems and components should be designed to be more efficient in their use of natural resources such as materials, energy and water'. The question aimed to assess general buy-in to the concept of resource efficiency and, via a comments facility, to identify potential explanations of respondents' answers. The affirmative response rate of 97% shows widespread buy-in to the broad concept of resource efficiency with two qualifications. The first is that by choosing to participate in a survey explicitly about resource efficiency, respondents may represent a self-selecting sample of people who support this concept. The second qualification is that support for a broad concept of environmental benefit may reflect current mainstream professional values in the construction industry rather than a special concern. An example of mainstream professional values is the view expressed in CIBSE's Guide A, that building services engineers, in carrying out their duties, should have 'due regard for the wider environment and producing a sustainable design' (CIBSE, 2015).

Comments were offered by a large majority (99%) of respondents in explanation to their answers. The most common theme was support for resource efficiency and sustainability, for example:

> *'As engineers we have an obligation to society to act sustainably, considering both resource and energy efficiency. As building services engineers we are in a unique position as the custodians of energy'* (Respondent B20, regional director, 22 years in industry).

Another theme was economic costs, referred to both by those who considered cost savings as a benefit of greater resource efficiency as well as by those who saw cost savings as a reason why resource efficiency was not prioritised, for example:

> *'By making systems more efficient we can get more power for the same amount of resources used. Or we can get the same power but at a lower cost'* (Respondent A7, trainee engineer, 1 year in industry).
>
> *'They [building services] currently appear to be optimised to balance running cost with capital cost, without much consideration of carbon'* (Respondent A6, associate director, 10 years in industry).
>
> *'The design of building services and systems is primarily driven by financial savings - even in the cases where sustainability is used as a way to increase the quality and/or value of the building... There is significant leeway to improve the environmental performance of buildings and that can be achieved using better incentives to encourage better use of natural resources'* (Respondent A12, façade engineer, 1 year in industry).

4.4.2 Effectiveness of activities to help achieve resource efficiency

Respondents were asked to rate the effectiveness of an extended list of activities in helping to achieve resource efficiency based on the seven categories used in the WRAP definition of resource efficiency in the built environment (WRAP, 2017), as previously listed in Table 2.1. The categories were slightly modified to refer specifically to building services. Two additional options were added related to building information modelling (BIM) and economic cost, to obtain feedback on the policy view that BIM is associated with reductions in cost and material waste in construction projects (HM Government. 2013, 2015). The responses shown in Figure 4.3 indicate firstly that for all 9 options, more respondents saw them as being effective rather than ineffective. For 7 of the 9 options, over 50% of respondents also believed them to be 'quite' or 'very' effective. The top ranking in importance given to operational energy and water efficiency may reflect the current focus in policy and practice on operational energy consumption, as identified earlier in the literature review. However, the third and fourth highest ranked options concern reducing embodied energy and carbon – clearly pinpointed as being effective by around 80% of respondents. Of the options ranked lowest in perceived effectiveness, cost minimisation is not seen by the majority as a way to use natural resources more efficiently. Conserving resources with scarcity and security issues is seen as the least effective of the seven WRAP activities. The proportion of neutral answers to this option is 2-5 times greater than the proportion of neutral answers given for the four options most likely to be seen as 'very effective' in Figure 3.4. Similarly, the neutral responses of 39% of respondents on the effectiveness of BIM may indicate that industry practitioners are also not yet convinced by policy messages about the environmental potential of BIM. This does not seem to be associated with a lack of knowledge about BIM, as 85% of these neutral responses selected 'neither effective nor ineffective' rather than 'don't know'.

When the responses are considered by sub-group, the only statistically significant difference in responses on any of the options is that respondents involved in designing building services, who make up 71% of the sample, are less likely than others to consider that BIM is an effective means to promote resource efficiency. Only 38% of building services designers compared with 75% of others consider BIM to be 'quite' or 'very' effective for this purpose, while 44% of designers compared to only 25% of non-designers gave neutral answers. This is interesting, as building services designers are more likely than non-designers to have practical experience of using BIM as a design tool.

Very ineffective	Quite ineffective	Neither effective nor ineffective/don't know	Quite effective	Very effective

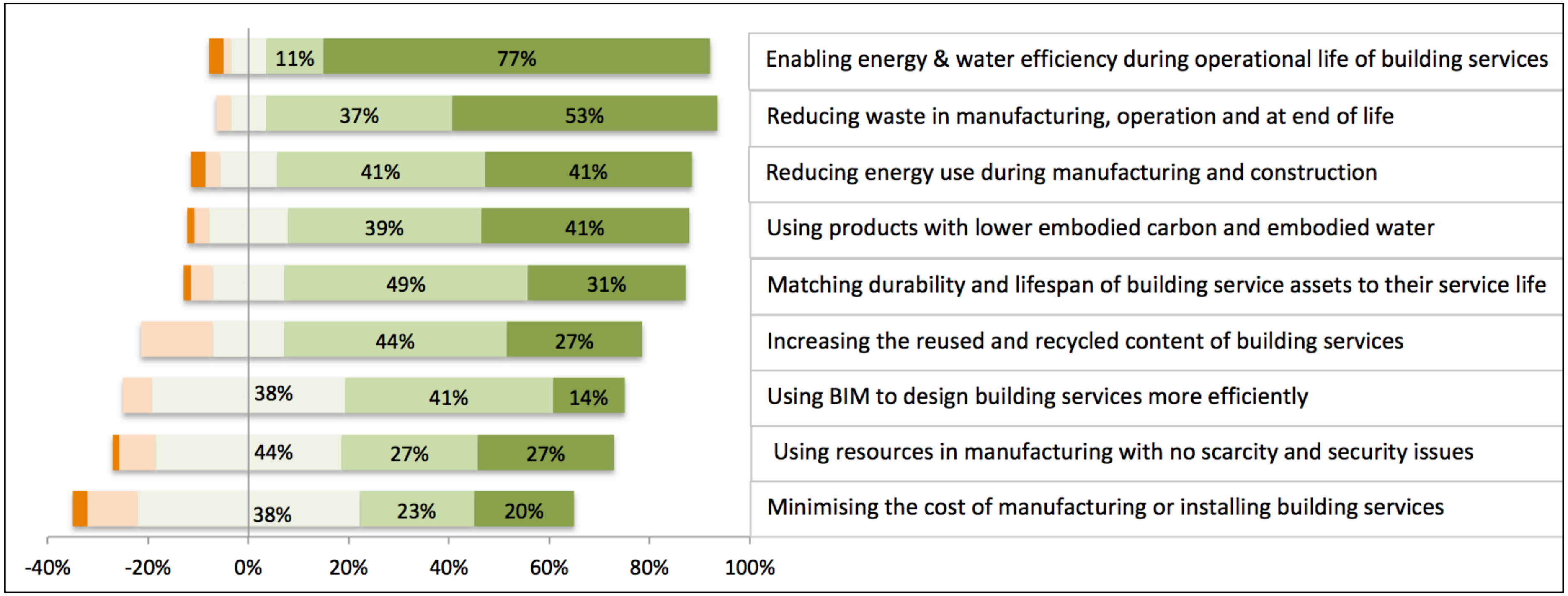

Figure 4-3: Effectiveness of activities to achieve resource efficiency

4.4.3 Influence of stakeholder groups on resource efficiency

Respondents were then asked to identify the three stakeholder groups considered to have the most influence on whether building services were efficient in their use of natural resources. The question did not specify the stage of building or service product lifetime to which this related, allowing answers to cover all lifetime impacts. Also, the preset options for stakeholder groups were not exclusive, as an option was provided to add other groups if applicable in a comments field. The request to select three groups was designed to explore the view from background literature and scoping interviews that building design was a collaborative process. In such a process it might be expected that design decisions with major environmental implications would be informed by the preferences of multiple stakeholder groups. The question was therefore phrased in such a way as to identify the groups most involved in such a collaborative process, rather than to identify a single stakeholder group most able to influence an environmentally positive outcome.

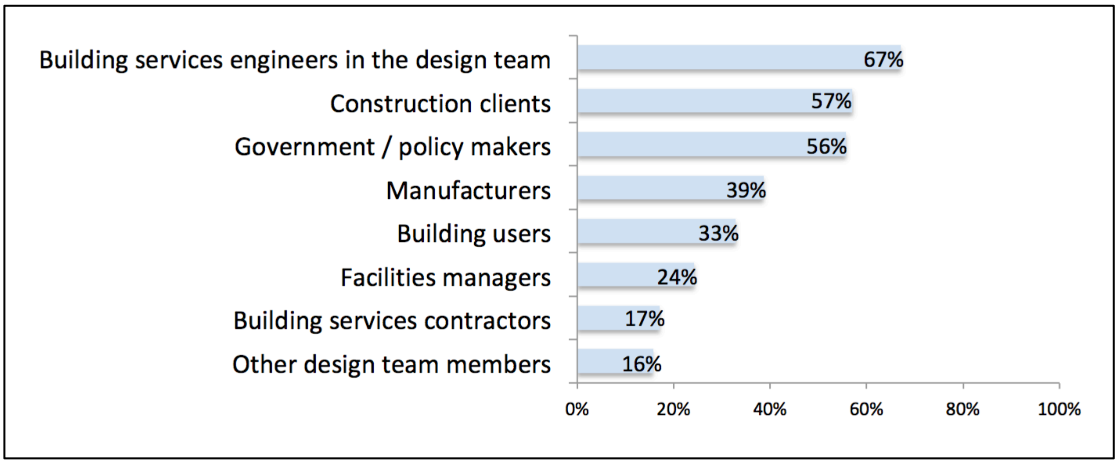

Figure 4-4: Influence of stakeholder groups on resource efficiency

Responses to the question (shown in Figure 4.4) suggest that stakeholder groups perceived to have most influence are building services engineers (BSEs), closely followed by clients and government/policy makers. This suggests that engineers see themselves as having only marginally more influence than the other two groups on the environmental impact of the building element for which they are most responsible. There were no statistically significant differences between sub-groups in the ranking of groups provided. This indicates that the tendency to identify BSEs as having the most influence was not restricted to respondents who identified themselves as BSEs. The following comments provided by respondents helped to explain the perceived influence of clients and policy makers:

> *'Most services engineers would like to design more sustainable building services systems but stumble upon cost limitations imposed by the clients. That is the point where government or policy makers can make a significant difference by raising the standards and increase the use of natural resources through legislation'.* (Respondent A12, façade engineer, 1 year in industry)

> *'As the specifiers, building services engineers are restricted to the client's requirements and budget, whilst we can try to influence their decisions in relation to energy efficiency we ultimately have to abide by their requirements UNLESS there is a regulation in place which takes precedence'* (Respondent A26, senior engineer, 13 years in industry).

> *'Designers can only work with what they are given. Modern contracts force in-efficiencies by ensuring that systems are oversized at an early stage for cost certainty and to ensure that the designer doesn't get sued for non-compliance'* (Respondent B6, associate director, 12 years in industry).

> *'Client decides how to spend the money, without that nothing happens. The engineers can design & specify efficient systems. The government can force the client decision by means of laws'* (Respondent C10, mechanical services engineer, 40 years in industry).

The implications for other research objectives are as follows. Building services designers appear to operate in a constrained environment in which other parties have a substantial influence on their ability to make resource efficient design decisions. This supports more detailed investigation of design decision-making processes via the qualitative study associated with research objective 3.

4.4.4 Importance of design activities in promoting resource efficiency

Respondents were asked to rank the importance of four design-related activities that might affect the resource efficiency of the building services systems and components for a given building project. The aim of the question was to reveal industry perspectives on what might constitute effective approaches with regard to the targeting of future interventions to support resource efficiency. These perspectives could be used to help align the proposed embodied carbon estimation method with the practical context in which decision support would need to be implemented. The design activities explored by the question had been identified from scoping interviews and background literature as those most influential over the final choice and/or design configuration of building services systems at project level. The results, shown in Figure 4.5, represent choices not just by building services engineers but also by construction clients, architects, structural engineers and building services contractors. While these choices may be made for many reasons, not all of which concern environmental impacts, they also determine the type and quantity of raw materials consumed by the building services as well as the associated embodied carbon.

All four design activities are seen by over 70% of respondents as 'very important' or 'quite important', while the ranking of the options suggests that activities are seen to have relatively more influence if their impact is more strategic and/or takes place earlier during the building design process. There were no statistically significant differences between sub-groups of respondents in their ranking of the options in this question.

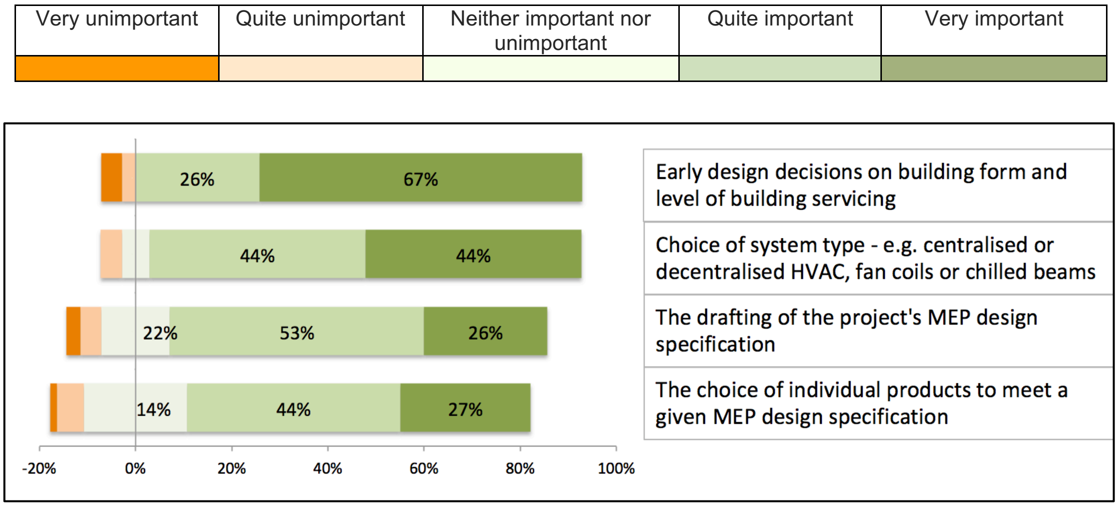

Figure 4-5: Importance of design activities in promoting resource efficiency

These responses have implications for several research objectives. For research objective 3, the importance placed on earlier and more strategic design decisions as a means to influence resource efficiency supports further investigation of how these decisions are made and by whom. For research objectives 4 and 5, the implications for the proposed HVAC system selection tool are that such a tool should ideally support comparisons between different levels of servicing, such as natural versus mechanical ventilation, as well as between different types of servicing systems and individual products.

4.4.5 Importance of key priorities when specifying building services

Respondents were next asked about the priorities that influenced choices made in specifying building services systems and products for a building project. Unlike the previous question, this question focused solely on factors that might be considered by design teams in producing a building services specification for a project. Of the available response options, eight reflected the WRAP categories of activities to promote resource efficiency (WRAP, 2017), but three other priorities of performance, reliability and economic cost were added to reflect issues identified from scoping interviews and background literature as being key general factors influencing choice in building services design.

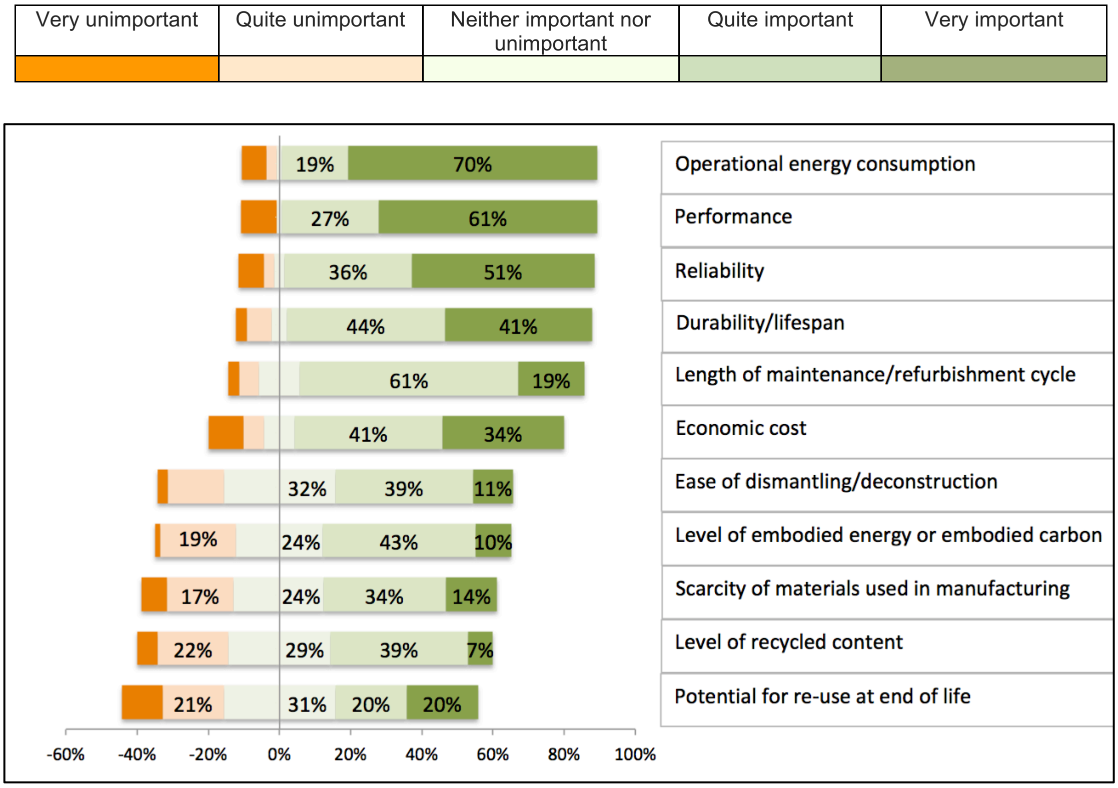

Figure 4-6: Importance of various priorities when specifying building services

The issue rated as most important by respondents was operational energy consumption, surpassing even performance and reliability, which are the next two issues in order of importance, as shown in Figure 4.6. Economic cost is the sixth out of eleven issues in order of importance, an interesting choice given the significance of cost constraints mentioned in comments to question 5. While this question sought views on the relative importance of a broad list of priorities that might inform a specification for building services, a previous question (responses to which were shown in Figure 4.3) examined perceptions on the relative effectiveness of activities aimed specifically at increasing resource efficiency. A comparison of responses to the two questions shown in Figures 4.3 and 4.6 shows key similarities and differences, although the questions are not completely equivalent. While operational energy consumption is seen as the most effective or important option in responses to both questions, only 3 out of 7 other options associated with resource efficiency in the question on specification are seen by a majority of respondents as ‘quite’ or ‘very’ important. In contrast, in the question not linked to specification, all 7 options associated with resource efficiency were seen as 'quite' or 'very' effective by a majority of respondents. This suggests that environmentally beneficial choices may be seen as less important as criteria on which to base the choice of a specific building services design than when considered in a more abstract sense as aspirational goals. Another interesting feature of the responses to the question on specification shown in Figure 4.6 is that while embodied energy or carbon is seen as 'quite' or 'very' important by a slight majority (53%) of respondents, product durability and lifespan is seen as 'quite' or 'very' important by 85% of respondents. This is important because products that are more durable or longer lasting can have lower embodied impacts over the life cycle due to a less frequent replacement or renewal cycle, provided that these are not offset by a more energy intensive manufacturing stage (CIBSE, 2014).

The main implication of these responses for the research objectives is that multiple determinants of product choice matter to building services designers, who represented 70% of survey respondents. Among these, embodied carbon is of moderate importance, but this rises if it is seen through the lens of product durability and lifespan. This supports the decision to focus on embodied carbon in research objectives 2 and 3 and the further investigation into design choice required by research objective 4, as well as helping to inform the context in which an HVAC selection tool would be used in practice, as required by research objective 5.

4.4.6 Importance of LCA impacts of building services

The next question sought views on life cycle impacts of building services in a slightly different way, by asking respondents how important a number of priorities were in a 'typical construction project'. This was to distinguish perceptions of the priority given to environmental impacts within what was perceived as standard practice in the construction industry as distinct from priorities within the opinions of survey respondents. The pattern of responses shown in Figure 4.7 contrasts with those given to the previous scale item question.

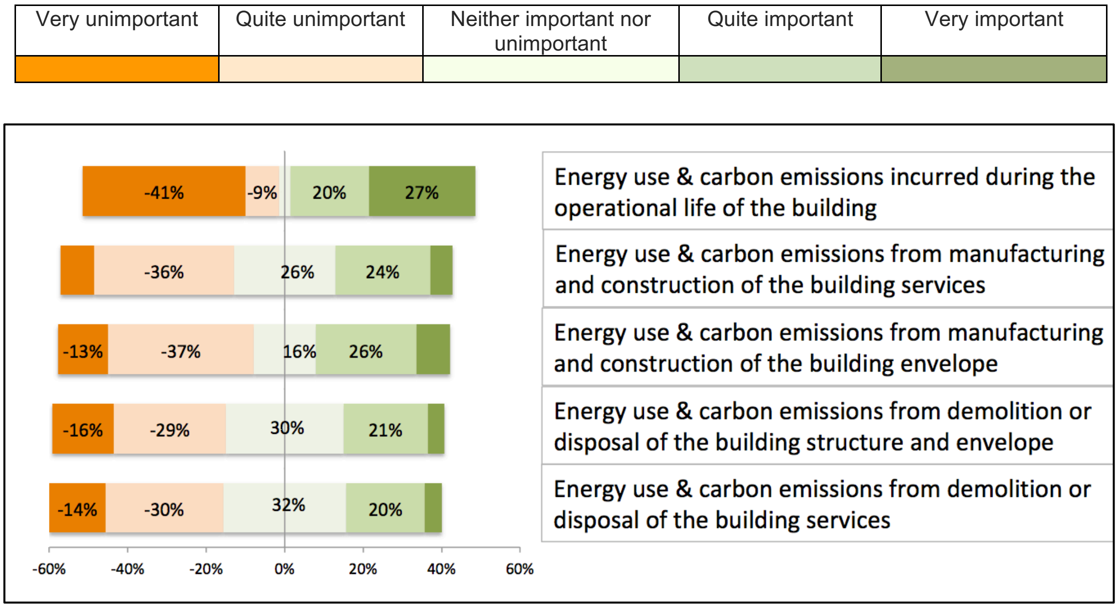

Figure 4-7: Importance of different types of LCA impacts of building services

Firstly, a greater proportion of respondents considered that all five options representing life cycle impacts were 'unimportant' as opposed to 'important' in a typical project. Secondly, while operational energy use and carbon emissions were seen as 'quite' or 'very' important by a greater proportion of respondents than any other option, they were also seen as 'very unimportant' by a higher proportion of respondents than any other option, as views on this option were more polarised than views on the other four options.

A comparison of responses to this and the previous question shows similarities and differences in terms of the response profile and scale categories selected. Almost twice as many respondents thought that operational energy was important 'when specifying' building services in the previous question (shown in Figure 4.6) compared to those who thought that 'operational energy and carbon' was important in a 'typical construction project' in the current question (shown in Figure 4.7). Similarly, while 53% of respondents saw embodied energy or carbon as important when specifying building services in the previous question (shown in Figure 4.6), only 24-30% in the current question (shown in Figure 4.7) considered that the options representing product stage and end of life embodied energy or carbon of the services were important in a typical project. This suggests in both cases that respondents saw their own practice as being more concerned about energy and carbon impacts than that of others with critical influence in the project teams of 'typical' projects.

As with the previous question, the responses to the current question also support further investigation into the complex nature of design choice as required by research objective 4. This is because designers must consider not only multiple factors influencing their own design choices but also the difference or tension between their own preference for environmentally beneficial options and what they see as the default preference of others in a 'typical' project.

4.4.7 Usefulness of an embodied carbon estimation tool

The final part of the survey sought views on a range of existing and possible interventions to measure embodied carbon. Respondents were asked whether they would find it useful to have a software tool that supported selection of alternative building services systems and components by embodied carbon values. An 'additional comments' field was included in order for respondents to explain their replies in further depth. In response, as shown in Figure 4.8, while almost two thirds replied 'yes', almost a quarter were 'unsure' and 11% indicated 'no'. These views on a specific solution may be contrasted with the more widespread support expressed in question 3 for the general principle that building services should use natural resources more efficiently. The comments provided by 86% of respondents helped explain the support expressed by the majority as well as the reservations held by detractors and some supporters.

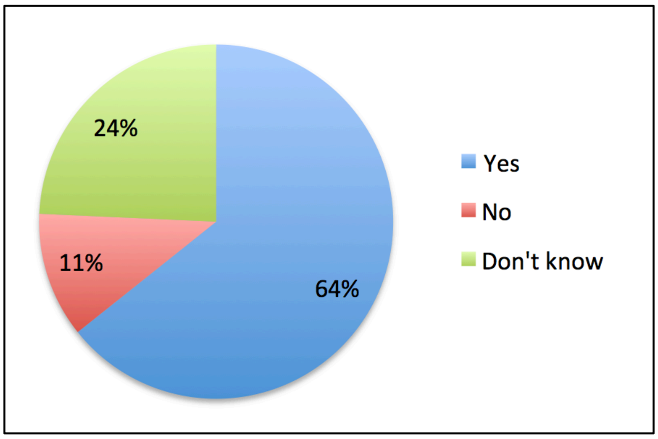

Figure 4-8: Usefulness of an embodied carbon selection tool

For many respondents, the reaction was that '*any tool that would provide more information on potential choices would be useful...'* (Respondent A3, associate director, 18 years in industry). Reasons provided included the view that '*clients, particularly public sector, often ask for this sort of information… not actually knowing what they're asking for and not knowing what to do with the answer'*, therefore a software tool would enable *'…a meaningful presentation to the client'* (Respondent A24, senior mechanical engineer, 8 years in industry). Other supportive responses added a note of caution, indicating that '*this would an excellent idea as long as everyone signs up to it'* (Respondent A25, MEP Revit technician, 32 years in industry), or that '*some degree of integration into the work we already do would be useful. Link it to operational carbon so the relative scales of each element can be seen'.* (Respondent B8, sustainability consultant, 6 years in industry). A recurring example of such integration suggested by respondents was that *'a financial cost comparison feature (both capital and operational) would have to be included to facilitate discussions with the contractor'.* (Respondent B5, graduate engineer, 4 years in industry). Many respondents who said the tool would be useful also commented on technical barriers such as there being *'no standard method of calculation'* (Respondent A4, principle engineer, 8 years in industry) or the possibility that the use of the tool to guide specification by designers could be nullified if *'the final equipment selection is made by the contractor'* (Respondent A10, associate director, 26 years in industry).

For the minority of respondents who expressed a neutral or negative answer on the usefulness of an embodied carbon estimation tool, answers were varied. Those giving neutral answers cited barriers in terms of the willingness of practitioners to act, such as the view that *'I'd find it interesting and probably use it to sway certain decisions, however I'm unsure it'll be used widely'* (Respondent C14, mechanical engineer, 2 years in industry). An elaboration of this point was the view that an estimation tool might not be widely used in practice '*…unless it was a statutory requirement (e.g. part of Part L)'.* (Respondent B2, regional director, 20 years in industry). The reference here is to the UK building regulations relating to conservation of fuel and power (HM Government, 2016). Some respondents giving negative answers cited a perceived lack of importance of embodied carbon, either because *'I don't think may people care… right now in the business world'* (Respondent C13, research engineer, 4 years in industry) or because *'performance of a component is much more important that the embodied carbon. Therefore I would ignore the results if the component still had poor performance compared to another component'* (Respondent A7, trainee engineer, 1 year in industry). Another questioned the quality and enforceability of a tool, saying that '*I would question the data, probably wouldn't trust the data…'* and that *'without including any minimum embodied carbon performance standard within the specification the contractor could select alternative products'.* (Respondent A22, principal engineer, 12 years in industry). This elaborated on the view expressed by Respondent A10, who conversely thought the tool would be useful but also saw contractor discretion as a barrier.

These responses support research objective RO5, which concerns the specification for an embodied carbon estimation tool, by providing more detail on user requirements such as the need for the tool to include operational carbon and cost and the need for data to be reliable enough to be trusted by users.

4.4.8 Ways to measure embodied and whole-life carbon

The next question aimed to assess views on interventions to measure embodied or whole-life carbon at a broad and detailed level. The responses shown in Figure 4.9 show almost 90% of respondents in support of the need to measure both embodied and operational carbon in principle, but variable levels of agreement on the merits of particular intervention measures. The proportion of neutral and 'don't know' answers for the named interventions varies between 21-69%, indicating that less is known about some interventions than others.

There is a clear contrast in responses between two generic alternatives, building regulations and voluntary incentives, with a clear majority agreeing that the former can help promote embodied carbon measurement and opinions being evenly divided for and against the utility of the latter. An important qualification here is that respondents were likely to have been aware that building regulations in the UK had so far only addressed operational rather than embodied carbon emissions. Responses to this question should therefore be seen as an affirmation that building regulations could potentially drive up measurement of embodied carbon if this was included within their scope. Comparing views on environmental product declarations (EPDs) and full life cycle assessments (LCAs), a majority of neutral answers on the former suggests that too little is known about EPDs for most respondents to express a positive or negative view. For those able to express a non-neutral choice, respondents were 7 times more likely to agree than disagree that full LCAs were a reliable way to assess life cycle impacts and twice as likely in the case of EPDs.

Very ineffective	Quite ineffective	Neither effective nor ineffective/don't know	Quite effective	Very effective

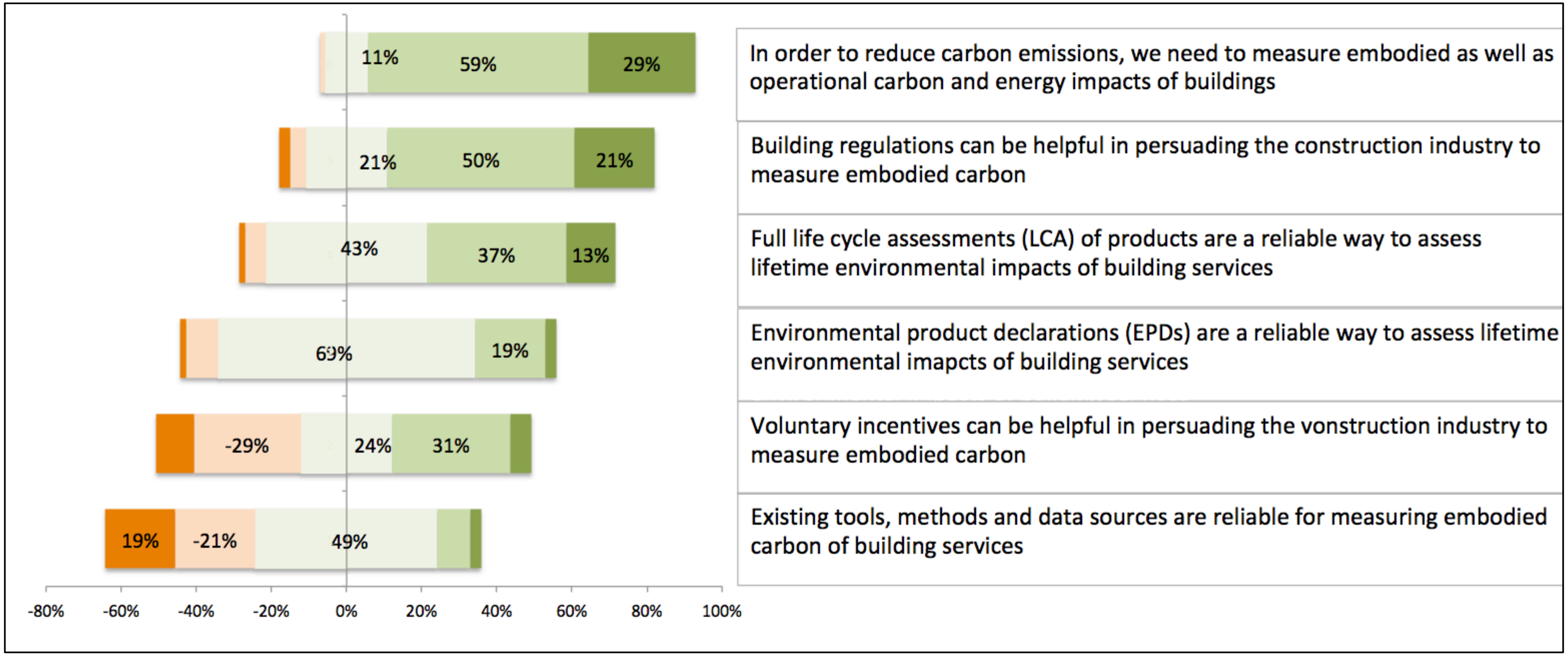

Figure 4-9: Views on ways to measure embodied and whole-life carbon

There are several implications of these responses for the current study's research objectives. The finding that most respondents believe embodied carbon should be measured while only a minority consider available methods, tools and data reliable for that purpose indicates that the methods and tool developed by this research must demonstrate reliability in a way that is meaningful to practitioners. At the same time, the belief of 50% of respondents in the reliability of full LCA studies supports the decision to ground any new approach in LCA methodology. If the term 'reliability' is used according to the ASHRAE online definition, where it refers to the 'probability that an instrument's repeatability and accuracy will continue to fall within specified limits (ASHRAE, 2018), then a method to estimate embodied carbon for generic building services systems would need to be applicable consistently across real world design environments where specific systems were being considered.

4.5 Discussion

4.5.1 Barriers and drivers linked to embodied carbon estimation

4.5.1.1 Attitudes

Reflecting on the significance of these findings for the research objectives, the first objective is to use the survey to identify attitudinal, knowledge-related and technical barriers and drivers associated with the calculation and reduction of embodied carbon in building services. For this discussion, attitudes are defined either as personal views expressed by survey respondents in their answers or views attributed by respondents to other stakeholders. Levels of knowledge about a topic may be approximated by the proportion of 'don't know' answers in questions on a topic where a 'don't know' option is available. Technical barriers and drivers may describe non-human factors that help or hinder embodied carbon reduction.

Responses to the initial questions on whether building services ought to be more environmentally resource efficient and the perceived importance of various activities that might help achieve this goal (shown in Figure 4.3) show that attitudes of practitioners are supportive, both generally and in relation to most of the interventions listed. While increasing operational energy and water efficiency is seen as the most effective means to make building services resource efficient, a majority of respondents (80%) also believe that reducing embodied carbon or water in building services is effective. In contrast, attitudes of respondents are mixed towards the utility of specific incentives and methods for embodied carbon mitigation when asked, as shown in Figure 4.9. This appears to reflect personal experience in that UK building regulations, which are seen as potentially useful by 71%, are widely perceived as having been effective in encouraging operational carbon reduction, despite not yet having been extended to regulate embodied carbon.

Taking the survey responses at face value, which means assuming no social desirability bias, (a feature of surveys in which people respond to questions in a way that over-reports 'good' behaviours for themselves (Ruane, 2016, p166)), the attitudes of 'others' in the construction industry are perceived to present a barrier to embodied carbon measurement. This is seen clearly when comparing responses to the two questions that sought respondent's own views on the importance of a broad list of criteria when specifying building services (shown in Figure 4.6) and their perceptions of the level of priority given to a list of environmental criteria in a 'typical' construction project (shown in Figure 4.7). The comparison shows that respondents rate the importance of embodied and operational carbon more highly than the level of importance these areas would have in a typical construction project.

Responses and comments associated with the question on the influence of various stakeholder groups in making building services resource efficient (shown in Figure 4.4) also suggest that the attitudes of influential stakeholders other than building services designers, such as clients, may preclude action on resource efficiency. A slightly different interpretation emerges as a common theme from comments added in response to the question on the usefulness of an embodied carbon estimation tool. In this case a view emerges that incentives would be needed to ensure take-up by building services engineers of such a tool. As 70% of the respondents define themselves as 'designers of building services', this implies that some survey respondents would also need a range of compelling incentives to encourage use and application of an embodied carbon estimation tool.

4.5.1.2 Knowledge-related and technical issues

Concerning knowledge-related barriers and drivers, the survey results suggest areas in which respondents were relatively lacking in knowledge, via an analysis of neutral responses. In the two closed questions with options of 'yes', 'no' or 'don't know', the proportion of don't know responses can be assessed, along with the reasons given in the comments field for the answer. In the scaled questions including 'neither' and 'don't know', the proportion of 'don't know' responses can be viewed as indicative of gaps in knowledge. For scaled questions with one neutral point indicating 'neither', it is difficult to infer such a lack of knowledge, as this type of answer may also signify indifference, a balanced view or having no opinion (Willits et al, 2016). Using this approach, there is only one question in which a gap in knowledge of the topic seems particularly relevant/important. This is the question that considered specific interventions aimed at reducing embodied carbon, for which results are shown in Figure 4.9. The finding that 40% of respondents indicated 'don't know' when asked to rate the reliability of environmental product declarations (EPDs) suggests a knowledge barrier, probably associated with the scarcity of available EPDs of building services products, as discussed earlier in section 2.5.4.

Technical barriers and drivers associated with estimating embodied carbon were not the subject of a single closed question. Instead they addressed by optional comments from respondents who were invited to explain their answers to the question on whether an embodied carbon tool for building services would be useful. The three main themes that emerged in the responses were technical challenges, incentives that might be needed and the benefits the tool might offer.

As this topic relates to research objective 5, it is discussed below in section 4.5.4.

4.5.2 Supporting the embodied carbon estimation method

The second research objective entails developing an estimation method for embodied carbon of composite building services components, incorporating uncertainty analysis, with a focus on the product stage, or cradle to gate phase of embodied carbon. The survey findings support this objective in four ways. Almost 90% of respondents believe that embodied as well as operational carbon needs to be measured in order to reduce emissions. Around 80% of respondents believe that using products with low embodied carbon and reducing energy use in manufacturing and construction are effective ways to promote resource efficiency. Over half of respondents believe that embodied energy and carbon impacts are important when specifying building services and nearly two thirds would find a tool helpful that supported their ability to estimate those impacts.

4.5.3 Supporting the study of design decision-making

There are four areas of the survey findings that inform the need to implement a further, qualitative study of decision-making by building services designers. The first is the influence of other stakeholders such as construction clients on whether a building services design is resource efficient, seen in the response to the question on this topic. The second is shown by the response to the subsequent question on the relative importance for resource efficiency of earlier and more strategic design decisions, which also are influenced by other stakeholders in building design. The third is the varying importance of multiple factors, not all environmental, for designers when writing a building services specification, as seen in responses to the question shown in Figure 4.6. The fourth is the relative contrast between the importance placed by building services designers on embodied and operational carbon emissions and the perceived lower importance of these issues on a typical project. These issues together indicate a complex environment in which the ability of a building services designer to recommend a resource efficient design option backed by evidence of environmental impacts is only one of many factors that may influence the design chosen.

4.5.4 Supporting the specification for an embodied carbon estimation tool

The fifth objective of this research is informed by the response to the question on whether respondents would find an embodied carbon estimation tool for building services useful. The specification for the tool is also informed by responses to the question that considers the timing of design interventions to support resource efficiency, which are shown in Figure 4.5. These indicate that the tool may need to be capable of supporting strategic decisions about servicing levels and system type as well as product level choices. At the same time, responses to the question on priorities when specifying building services (shown in Figure 4.6) indicate that the tool must support choice in the context of competing criteria, not all of which are environmental. Above all, the tool needs to address the requirements of its users to be practicable. This point is reinforced by comments made in response to the question on whether an embodied carbon estimation tool would be useful. Thematic analysis of these comments identifies three recurring themes of technical challenges such as concerns on data quality and the lack of standard calculation methods, the need for incentives to promote take-up and the benefits the tool might offer. Respondents' comments shed further light on these requirements:

> *'Nice to have, but keeping cost data and economic models up-to-date is very difficult, and the joined up thinking required from software are users make it very difficult for such a piece of software to be developed and maintained'* (Respondent B7, associate director, 19 years in industry).
>
> *'Clients would love this. Could influence specifications'* (Respondent A17, graduate mechanical engineer, 3 years in industry).
>
> *'Embodied carbon is... consistently overlooked. A tool to force designers and contractors to consider this would be useful. However, whether it would be accepted and utilised effectively is another issue. Based on the typical perception of other tools such as BREEAM... it may be difficult to get engineers to use such tool. Engineers would have to buy in to and support the idea otherwise there will be no value and the tool would be seen as an extra job people don't want to do'* (Respondent B18, sustainability consultant, 5 years in industry).

'Would be interesting but I think it unlikely to be widely used or any decisions made on its outcome unless it was a statutory requirement (e.g. part of Part L)'. (Respondent B2, regional director, 20 years in industry).

4.5.5 Limitations of the survey

As a mainly quantitative component within a mixed methods research design, this survey is firstly subject to threats to validity of three types, internal validity, external validity and reliability (Bryman, 2012, Yin, 2014). A key threat to external validity of this kind of survey would be that the sample might be either too small to support adequate statistical analysis or not sufficiently representative of the target population. In this case, the sample size achieved was large enough to support testing of significant differences in responses between sub groups. The fact that the target population was not the general construction workforce, but construction practitioners involved in some way with building services systems, makes it difficult to find a demographic or occupational profile of the target population against which to compare the sample. The reliability of the survey, which refers to its ability for the measurement method to be replicable elsewhere, does not present a major challenge.

The internal validity of the survey depends on the fitness for purpose of the measurement instrument as well as the design of the questions. In this case, the choice of an established method, multi-indicator Likert questions, enabled in most cases the detailed identification of views on the chosen topics. However, there was one instance, question 11, in which additional comments from respondents indicated that the question design seemed ambiguous, therefore the responses to this question were not included in the analysis.

4.6 Chapter summary

A survey of UK-based construction industry practitioners working in the building services sector has provided insight into all of the five research objectives of this thesis. The findings show that a group of construction practitioners of whom 70% are designers of building services have particular views in relation to the topic area of this study. They strongly support, for example, resource efficient practice for the building services with which they work and they clearly do not see this as limited to reductions in operational energy and carbon impacts. However, the survey respondents face certain challenges in their ability to implement resource efficient practice in building projects, including the timing of design decisions, the priorities of other stakeholders and the competing demands of multiple environmental and non-environmental design criteria. The respondents have mixed views about the effectiveness of methods or incentives that support measurement of whole-life or embodied carbon and energy impacts and consider that an embodied carbon estimation tool for building services would be beneficial whilst also needing to resolve technical challenges and provide sufficiently compelling incentives to encourage widespread take-up.

5 Embodied carbon estimation and uncertainty

5.1 Introduction and objectives

This chapter addresses the second and third research objectives, RO2 and RO3 which are respectively to develop an estimation method for embodied carbon (EC) of composite building services components that addresses uncertainty of input parameters (RO2) and to apply that method to the comparison of EC of alternative building services systems, initially focusing on HVAC systems. A case study-based methodology is outlined, in which life cycle impacts of HVAC components and building-wide systems used in office buildings are investigated, focusing mainly – but not exclusively – on product stage embodied carbon. The results of the case studies are then considered and discussed, initially as ingredients for a method to estimate embodied carbon deterministically and subsequently with the inclusion of uncertainty analysis. This is accomplished by testing an analytical method of uncertainty propagation against a sampling-based alternative. The validity, limitations and wider applicability of the combined estimation method are then discussed, after which a summary is provided of the chapter as a whole.

5.2 Methodology

5.2.1 Overview

This section outlines the general methodology used for investigation of case studies, while details of the specific LCA methods used are described in subsections 5.2.1-5.2.5 below. The methodology is illustrated schematically in Figure 5.1, using a modified version of the process diagram used to describe the framework of an LCA study in the ISO standard 14040 (BSI, 2006a, p8). The investigation combines a sequential use of case studies, shown in box A of Figure 5.1, with iterative use of the four-stage LCA framework shown in box B during each phase of box A. The direct application of the LCA results as research objectives of this study are then shown in box C. A key aspect of the LCA framework is circularity, in that it supports reflection after each LCA stage followed by revision or adjustment of previous stages where required.

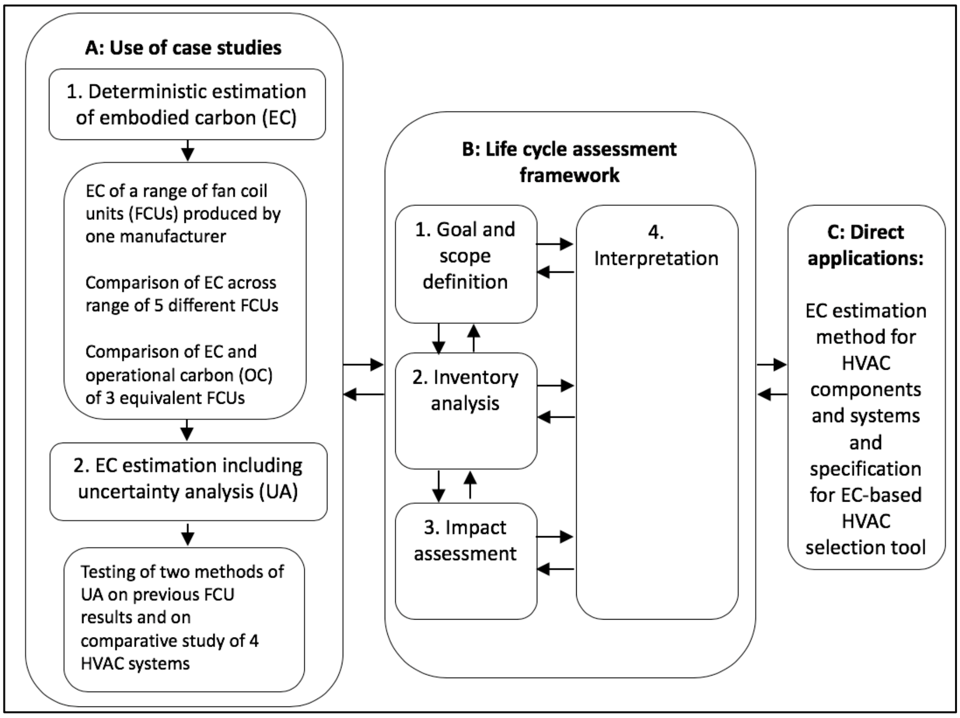

Figure 5-1: Methodology used for embodied carbon case studies (BSI, 2006a)

The case studies are investigated in two phases, as follows.

1. Deterministic estimation of embodied carbon (EC)
    - Product stage GWP impacts of an HVAC component, a fan-coil unit (FCU), are calculated using primary data on material and energy inputs for a full range of FCUs of varying cooling capacity made by a UK-based manufacturer, in order to ascertain whether EC can be estimated based on data on material type, mass and rated power.
    - The calculations are repeated across the product ranges of equivalent FCUs produced by four other manufacturers using similar raw materials, to test the consistency of this method in producing deterministic EC estimates.
2. Embodied carbon estimation with uncertainty analysis added:
    - Using the results of phase 1, uncertainty analysis (UA) using first-order analytical uncertainty propagation (AUP) and Monte Carlo simulation (MCS) is applied to compare the effectiveness of each

method in estimating the effects of input uncertainty on the predicted embodied carbon impacts of the FCUs.

- Estimates of product stage and operational EC impacts are then compared across different uncertainty scenarios for three FCU models of equivalent cooling capacity made by different manufacturers, to assess the relative significance of embodied and operational carbon over the economic life of the component.
- The two UA methods are applied to measured and estimated input data on other common HVAC components, enabling a comparison of product stage EC impacts of case studies of building-wide HVAC systems of two alternative types.

5.2.2 Goal and scope of LCA study

The goal of the study is to develop a method to estimate product stage embodied carbon impacts of alternative types of HVAC components and systems used in UK office buildings, incorporating uncertainty analysis of the effects on estimated impacts of uncertain life cycle inventory data. The method will be parametric in the sense that it develops an approach used by previous studies in which life cycle impacts of buildings and building elements are estimated by transforming the input parameters of a 'base case' (Basbagill et al, 2013, Moncaster and Symons, 2013, Ruuska and Hakkinen, 2014, Hawkins and Mumovic, 2017). However, it differs from these studies in that it is specifically aimed at HVAC components and systems. The method is intended to inform embodied carbon benchmarking and a specification for a pilot tool to compare HVAC system options at or before the 'concept design' stage of building design at which 'outline proposals' for building services systems are prepared (RIBA, 2013). Any product comparisons made in this study are used to give an indicative value of relative embodied impacts of generic HVAC options, rather than for 'comparative assertions to be disclosed to the public' about alternative products in the sense defined by ISO LCA standards (BSI, 2006b, p33). Identities of product manufacturers are therefore kept anonymous. The study uses a process-based LCA approach as this is the approach recommended for studies of building and building products in the relevant ISO standards (BSI, 2011, 2014).

This remainder of this section describes details of the LCA scope in terms of the product system, system boundary, functional unit or functional equivalent, cut-off criteria and allocation procedure.

5.2.2.1 LCA scope: Product system and system boundary

To match the five phases of the investigation of case studies outlined in the previous section, the scope of the product system is defined for an HVAC component and for a building-level HVAC system, shown respectively in Figures 5.2 and 5.3. The HVAC component is a fan coil unit (FCU) able to supply heated, cooled and conditioned air to part of a building, an example of which is shown in Figure 5.4. The HVAC system delivers all the functions of heating, ventilation and air-conditioning to an office building and is made up of multiple components. An example of a building-wide HVAC system that uses fan coil units is shown in Figure 5.5. The product system within the system boundary in Figures 5.2 and 5.3 contains information modules summarising the unit processes that transform inputs into outputs, with each module covering particular stages of the building life cycle defined by the relevant ISO standards (BSI, 2011, 2014). Figures 5.2 and 5.3 also show the major flows of environmental resources associated with each product system. The system boundary in Figure 5.2 includes the product (A1-A3) and operational (B6) stages of the FCU, although the initial investigation into embodied carbon impacts of FCUs focuses only on the product stage. The investigation into embodied carbon impacts of HVAC systems represented in Figure 5.3 focuses exclusively on the product stage.

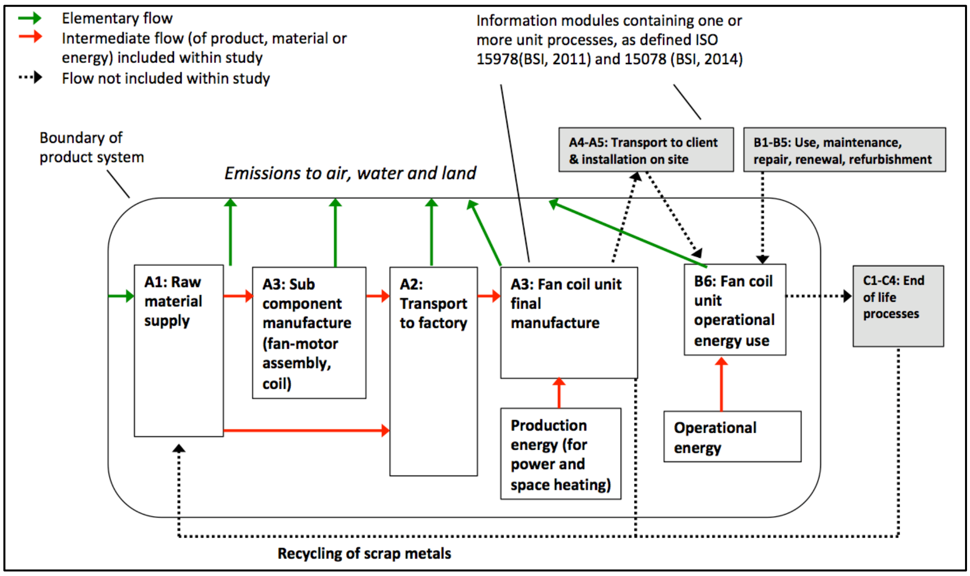

Figure 5-2: System boundary, processes and flows used in study of fan coil unit, based on ISO information modules as defined in BSI (2011, 2014).

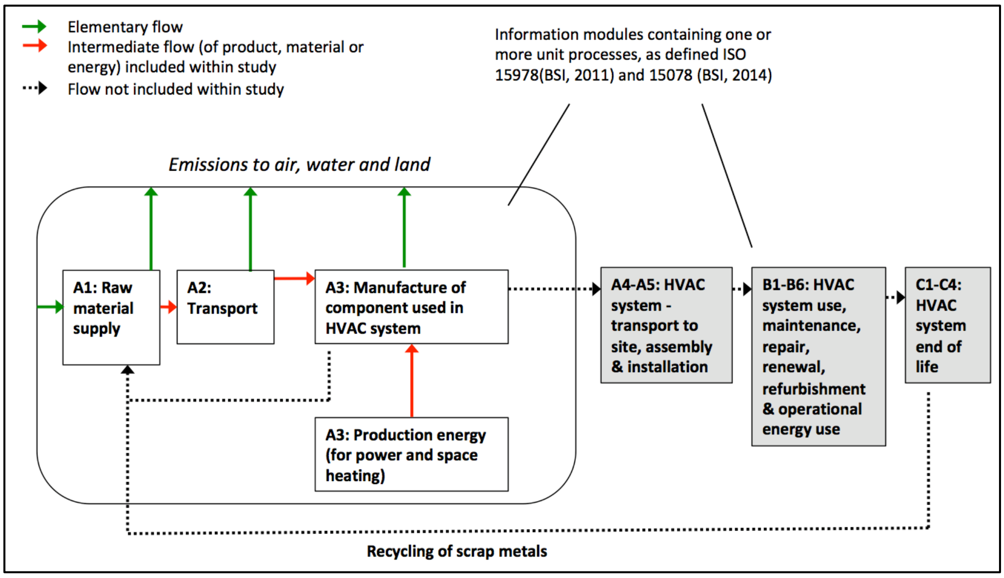

Figure 5-3: System boundary, processes and flows used in study of HVAC systems, based on ISO information modules (BSI, 2011, 2014)

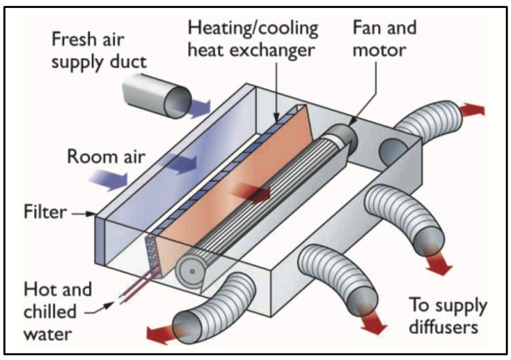

Figure 5-4: Basic configuration of a horizontal fan coil unit (BSRIA, 2013)

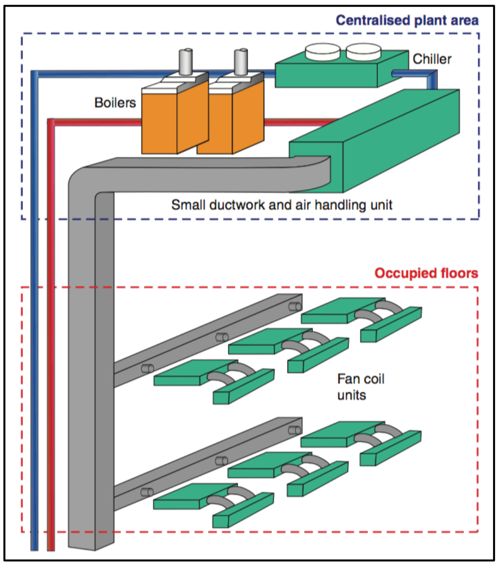

Figure 5-5: Example of partially centralised air-conditioning system (Oughton and Wilson, 2016)

5.2.2.2 LCA scope: Functional unit and functional equivalent

In order to compare life cycle impacts of alternate scenarios involving one product or different products, three types of functional unit or functional equivalent are used. Full definitions of each term are provided in Table 5.1.

Table 5-1: Functional units and functional equivalents used in case studies

Phase of investigation	Description
Phase 1 (deterministic study) and phase 2 (with uncertainty analysis added)	Functional unit *(defined as the 'quantified performance of a product system for use as a reference unit', BSI, 2014, p8):* The product stage GWP impact of a ducted, water-side fan coil unit (FCU) of total cooling capacity varying from 2 to 8 kW.
	Functional unit: The product stage and operational GWP of a single FCU, sized to meet a notional, maximum office cooling load of 2.5 kW for the equivalent of 25% out of 12 hours daily over 10 years.
Phase 2 (deterministic study) only	Functional equivalent *(defined as the 'quantified functional requirements and/or technical requirements for a building or an assembled system for use as a bases for comparison' (BSI, 2011, p9*). The product stage GWP impact of an installed HVAC system, measured in kg CO_2 equivalent per m^2 of gross internal floor area (GIFA) of an office building. An HVAC system is defined to fall within the standard cost categories 'space heating and air treatment' and 'ventilating services' (RICS, 2012) and to provide all the functions of heating, mechanical ventilation and air-conditioning for a building. The system must also meet the following thermal comfort standards set by the British Council for Offices (BCO, 2014): Internal temperature: 24°C ± 2°C (Summer); 20°C ± 2°C (Winter); Outside air replacement: 12-15 litres/second/person (BCO, 2014)

5.2.2.3 LCA scope: Cut-off criteria and allocation procedure

The cut- off criteria for the inclusion of input data used in this study are those recommended by ISO standard 15804, i.e. 1% of mass or energy inputs per unit process and 5% of inputs per life cycle module [BSI, 2014, p25]. LCA studies can be 'attributional' or 'consequential', respectively measuring impacts occurring either within the life cycle stage(s) studied or in the future (Buyle et al., 2013). Here an attributional approach is used, as this aligns with the approach of the LCI databases used, the Inventory of Carbon and Energy (Hammond and Jones, 2011) and Ecoinvent v.3.1 (Ecoinvent, 2014). For the same reason, allocation of co-products is measured primarily by physical quantity as recommended by ISO 14044 (BSI, 2006b).

5.2.3 Life cycle inventory analysis

The life cycle inventory analysis entails the 'collection and calculation of data to quantify relevant inputs and outputs of a product system' (BSI, 2006a). Key issues here are the sources, collection methods and quality of data. Table 5.2 summarises the data sources and collection methods used for the LCA study. Given the research objective of developing embodied carbon estimation methods to handle sparse or uncertain input data, the aim was to obtain the best quality primary data available. Detailed data was obtained for both phases of the case study investigation described in Table 5.2 from several HVAC equipment manufacturers on raw materials, production energy, transport and material waste in manufacturing. Through the work of the project sponsor, it was also possible to conduct an experimental 'tear-down' analysis on site of some components that had been stripped out of 'live' building projects, enabling measured data on raw materials to be compared with that provided by manufacturers and/or specified in designs. Primary data was also obtained on designs of HVAC systems in current and recently completed projects in which the project sponsor had been part of the design team.

Table 5-2: Data collection methods and data sources

Phase of investigation	Methods of data collection	Type of data by source
1. Deterministic embodied carbon (EC) estimation	Desk research Quantity take-off from design drawings and BIM models Field experiments on stripped out HVAC components in-situ using 'tear down' analysis	*Quantitative data on raw material types and quantities:* - Bills of materials and product literature from HVAC equipment manufacturers - Experimental measurements -Drawings, BIM models and equipment schedules from building designs -Type III Environmental product declarations and previous LCA research studies of HVAC components and systems *Quantitative data on embodied carbon coefficients:* -LCI databases (The Inventory of Carbon and Energy and Ecoinvent v.3.1) - DEFRA/DECC transport emission factors CIBSE guides
2. EC estimation with analysis of input uncertainty	Analysis of data already collected	All of the above, plus estimated measures of dispersion to represent input uncertainty for raw materials and embodied carbon coefficients

The use of multiple sources of life cycle inventory data informs investigation of parameter uncertainty associated with the embodied carbon intensity or mass of particular raw materials used in building services components. Sources of uncertainty about values for raw material mass can include the following:

- Variations between manufacturers in masses or proportions of each raw material used within the same type of component of a specified size and/or power rating.
- Variations in type or amount between components specified by building services engineers in a design and components procured and installed by building contractors to meet the design specification.
- Variations between raw material types or masses used in a particular component as described in a manufacturer's bills of materials and that of the same component measured using experimental tear-down analysis.

The quality of the life cycle inventory data is addressed by ISO standards covering the qualitative categories of age, geographical and technological accuracy of the data for building specific studies, (BSI, 2011) and additionally on precision, completeness, representativeness, consistency, reproducibility, sources and uncertainty for all LCA studies (BSI, 2006b). The following steps were taken to ensure compliance with the data quality standards for building-specific studies:

- **Age of data:** Both LCI databases used within this study, Ecoinvent v.3.1 (Ecoinvent, 2014) and the Inventory of Carbon and Energy (Hammond and Jones, 2011) meet the ISO requirement for generic datasets of having been updated within the last 10 years (BSI, 2014). UK government data on carbon intensity of the electricity grid and freight transportation were current when included in this study (DEFRA/DECC, 2015). Manufacturers' data on mass and energy inputs for HVAC components was also current when obtained. All datasets used were based on one year averaged data.
- **Geographical coverage:** As all HVAC components and systems considered in this study are manufactured in the UK or elsewhere in the EU, the data meets the requirement that 'the geographical coverage shall be representative of the region where the production is located' (BSI, 2011, p42).
- **Technological coverage:** An emphasis on multiple primary and secondary sources of data for HVAC components, as indicated in Table 5.2, ensures as far as possible that 'the technological coverage shall reflect the physical reality for the declared product or product group' (BSI, 2014, p27).

5.2.4 Life cycle impact assessment

The life cycle impact assessment (LCIA) should be planned to achieve the goal and scope of the LCA study and requires a choice of impact categories and characterisation methods (BSI, 2006b). Given the fact that a key research objective of this study is to develop an embodied carbon estimation method, the main environmental impact category considered is that used most widely to measure embodied carbon, Global Warming Potential (GWP), with a characterisation factor of 100 years (IPCC, 2013). The calculation used to estimate the product stage embodied carbon impact of an HVAC component or system is given by equation 5.1.

$$\mathrm{EC}_{cc} = \sum_{i=1}^{n}[mk_R] + \sum_{i=1}^{n}[mk_T] + \sum_{i=1}^{n}[mk_{MF}] \qquad \text{(Equation 5.1)}$$

In Equation 5.1, EC_{CC} = the product stage embodied carbon of a composite component, m = mass, and k_R, K_T and k_{MF} are the carbon coefficients for raw material supply, transport and manufacturing respectively, matching the product stage modules A1, A2 and A3 in the ISO standard (BSI, 2011, 2014), as shown in Figure 2.3. The coefficient k_T is the product of distance travelled and the carbon coefficient for the mode of transport, while k_{MF} is the product of energy used in manufacturing and the carbon coefficient for supply of electricity and/or heat..

5.2.5 Investigation of parameter uncertainty

The investigation of parameter uncertainty provides an additional layer of analysis to the life cycle impact assessment. The uncertainty analysis is applied exclusively to the assessment of GWP impacts arising from the product stage of the life cycle of HVAC components and systems, as these are the impacts most relevant to the research questions addressed in this study. The investigation addresses research question 2b, which asks how uncertainties in input parameters affect embodied carbon estimates of HVAC components and systems. While the method of uncertainty analysis described in chapter 3 enables an initial screening-out of input parameters with an insignificant effect on environmental impact using contribution analysis and sensitivity analysis, the uncertainty of all four input parameters from Equation 5.1 will initially be considered. The uncertainty analysis itself begins with uncertainty propagation alternatively using first order analytical uncertainty propagation (AUP) and Monte Carlo simulation (MCS). The AUP method is able to calculate both the output uncertainty associated with a particular input parameter and the contribution to overall output variance (CTV) of all input parameters using Equation 2.1.

$$Var[y] \approx \sum_{i=1}^{n} var[x_i] \left[\frac{\partial y}{\partial x}\right]_{X^0}^2 \qquad \text{(Equation 2.1)}$$

In Equation 2.1, the variance of output parameter y is approximately equal to the sum of the CTV of each input parameter x, which in turn is expressed as the product of the input variance of x and the absolute value of the partial derivative of y with respect to x. No covariance is assumed to exist between input parameters.

The MCS method, which draws pseudo random numbers from a set of input parameters with known probability distributions to produce a sampled distribution of an output parameter, does not also calculate CTV. However, CTV can then be calculated either by using linear regression (Morgan and Henrion, 1990, p208) or by AUP (Heijungs and Lenzen, 2014). In this study, AUP is used to calculate CTV, with a modified version of Equation 2.1:

$$CTV[y, x] \approx \sum_{i=1}^{n} var[x_i] \left[\frac{\partial y}{\partial x}\right]_{X^0}^2 \qquad \text{(Equation 5.2)}$$

Using AUP in this way does not contradict the aim of testing MCS against AUP as uncertainty propagation methods, because the test compares estimates of the uncertainty associated with particular inputs rather than the CTV of all uncertainties.

For the test, two types of probability distributions for uncertain inputs are used, a normal (Gaussian) distribution and a symmetrical triangular distribution. The triangular distribution represents a situation in which all that is known about the value of a variable is an upper and a lower limit and a 'best guess' for its nominal value, with the variance calculated using Equation 5.3.

$$Var = \frac{a^2 + b^2 + c^2 - ab - ac - bc}{18} \qquad \text{(Equation 5.3)}$$

A triangular distribution is therefore one way to model the relative lack of knowledge about values such as the masses of raw materials making up composite HVAC components. The normal probability distribution is used in the test as a default option to represent situations in which a sample of sufficient size is available to approximate the true population distribution of the variable. Other types of probability distribution used in in life cycle inventory databases include the lognormal distribution, which is used as the default distribution for the Ecoinvent life cycle inventory database (Frischknecht and Rebitzer, 2005), however studies have shown that the choice of distribution type does not have a significant effect on the results of LCA comparisons between products (Muller et al, 2017).

The measures of dispersion used to represent uncertainty of input parameters are as follows:

- The comparison of embodied carbon (EC) across the size and power range of fan coil units made by a single manufacturer uses a coefficient of variation (CV) of 10% with respect to mass of each raw material;
- The comparison across alternative scenarios of EC impacts between equivalent fan coil units of three manufacturers uses CVs of zero, 5% or 10% with respect to mass and product stage embodied carbon coefficients (ECC) of each raw material, as detailed below in section 5.4.5.2.
- The comparison of EC between four alternative HVAC systems uses CVs of 10% with respect to mass and product stage ECC of the aggregated total of each generic type of component per HVAC system.

These simplified values are broad estimates informed by multiple sources of parameter uncertainty that are identified during the inventory analysis, rather than being based on empirically sampled probability distributions for each parameter, which would not have been practicable.

5.2.6 Interpretation of results

The result of the sequence of case studies are considered collectively using analytical steps based on those recommended by ISO standards for LCA studies;

which are firstly to identify ‘significant issues’ based on the results of the life cycle inventory and impact assessment stages and, secondly, to carry out an evaluation of the findings that considers completeness, sensitivity and consistency checks (BSI, 2006b, p. 23). As these checks are aimed at addressing threats to validity in LCA studies, the evaluation will also consider whether any other approaches are needed to mitigate the broad range of threats identified in chapter 3. Following this the conclusions and limitations of the work presented in this chapter will be discussed.

5.3 Case study methodology

This section discusses the background to the identification of case studies interrogated and the specific methods used for data collection and analysis, following on from the more general description given in chapter 3.

5.3.1 Case study of fan coil units: Overview

To meet the research objectives, the choice of an HVAC component for a detailed case study needed to meet two criteria. It needed firstly to be composed of multiple raw materials for which detailed life cycle inventory data was not readily available in LCI databases or software and, secondly, to be widely enough used in HVAC systems to be relevant to a study of those systems. Fan coil units (FCUs) are composed of multiple raw materials, are regularly identified as one of the most common items within installed air-conditioning systems in the UK (BSRIA, 2015, 2017) and can be used in centralised, partially centralised and localised air-conditioning systems. The selection and sizing of FCUs by engineers and contractors is led by operational criteria such as cooling loads, noise limits and the ability to accommodate future increases in loads, as well as economic cost (CIBSE, 2008). The choice also must meet regulatory limits on operational energy use, as defined in specific fan power (CIBSE, 2008). Existing methods and data available to building services designers do not, however, permit selection of FCUs to be based on knowledge about embodied carbon impacts.

The type of FCU considered in this case study is a 'water-side' unit in which heating or cooling is modulated by varying the flow rate of hot or chilled water supplied, as this type of FCU represents 75% of the UK market (CIBSE, 2008). An example is illustrated in Figure 5.4. An analysis of product literature confirms the consistency of the main components and materials used in the construction of horizontal, ducted, water-side FCUs across multiple manufacturers. These are(a) galvanised steel casing lined with polyurethane acoustic foam, (b) fans and motors made mainly of steel, aluminium and copper and (c) heating and cooling coils made of aluminium and copper.

5.3.2 Case study of fan coil units: Data collection and analysis

Comprehensive data was obtained for the full range of FCUs produced by a UK-based manufacturer who had agreed to participate in the research on materials and sub components used, supplier locations, transport methods from suppliers and energy used in production. A small number of relatively minor fixings and electrical components were excluded owing to gaps in manufacturers' data, but these were known to equal less than 0.5% of the mass of an entire FCU and therefore able to be excluded from the inventory analysis under the cut-off rules. The material data was combined with reference data on the carbon intensity of raw materials in order to calculate carbon coefficients, thus enabling the embodied carbon content of each FCU across the range to be calculated. Table 5.3 shows the carbon coefficients and sources that were used.

Table 5-3: Embodied carbon coefficients used for case study of fan coil units

Raw material or process input	Embodied carbon coefficient	Source
Fan coil unit casing - Galvanised sheet steel, UK/EU recycled proportion of 59%	1.54 kg CO_2 e / kg	Hammond and Jones, 2011
Fan coil unit casing Polyurethane insulation foam	4.84 kg CO_2 e / kg	As above
Coils - General aluminium, UK typical value	9.16 kg CO_2 e / kg	As above
Coils - Copper - tube and sheet, UK/EU recycled proportion of 37%	2.71 kg CO_2 e / kg	As above
Fan/motor assembly - General steel, UK/EU recycled proportion of 59%	1.46 kg CO_2 e / kg	As above
Fan/motor assembly - - General aluminium, UK typical value	9.16 kg CO_2 e / kg	As above
Fan/motor assembly - Copper - tube and sheet, UK/EU recycled proportion of 37%	2.71 kg CO_2 e / kg	As above
Electricity used in UK manufacture of FCU	0.394 kg CO_2 e /kWh *and* 0.18 kWh/ kg	BEIS, 2015
Natural gas used in UK manufacture of FCU	0.185 kg CO_2 e /kWh *and* 0.01 kWh/ kg	DEFRA/DECC, 2015
Transport from UK suppliers to factory gate	0.114 kg CO_2 e /tonne km	DEFRA/DECC, 2015

Product details were then obtained from websites of other UK-based manufacturers of horizontal, ducted FCUs with dimensions of between 250-300mm in depth, a standard type installed in ceiling voids in office buildings. Of these, four models from different manufacturers were selected that had been tested against the same standard conditions, namely external static pressure of 30 Pa, chilled water flow/return temperatures of 6°/12°C, summer air temperatures of 23°C and relative humidity of 50%. A comparison was then made of the ratio between the relative mass and total cooling capacity of each FCU by size and by manufacturer, using an approach followed in a previous environmental study of air-conditioning systems (Riviere et al, 2012a). Assuming consistency of raw materials between manufacturers, the embodied carbon intensity of FCUs in relation to total cooling capacity was compared by manufacturer.

5.3.3 Case study of HVAC systems: Overview

The definition of a functional equivalent set out in Table 5.1 for the comparison of HVAC systems requires that each system provides services able to meet specific thermal comfort criteria. This enables embodied carbon impacts of systems of different technical types to be compared. In selecting case studies, it should be noted that this definition omits some complexity about identification of installed HVAC systems. Firstly, there is no universally agreed method to classify systems that provide all of the functions of heating, mechanical ventilation and air-conditioning. Systems can be classified as centralised, partially centralised or local, based on the location of their main components and/or by their technological differences, although system configurations can exist that are not easily classified by either method (Oughton and Wilson, 2016). Secondly, a building may contain more than one generic type of HVAC system, each serving different zones or floors. To ensure that HVAC systems can be compared using the functional equivalent definition provided in Table 5.1, the case studies used in this study are of office buildings each of which has a single generic type of HVAC system installed.

It is also relevant that perfect compliance with the defined functional equivalent would require that the impacts of alternative HVAC systems could be compared with respect to the same building, as the form and function of individual buildings may influence the type or configuration of systems that can be installed. In LCA studies this is normally only possible if a notional identical building is assumed (Chen et al, 2012), as practical examples of two or more identical buildings with different HVAC systems are hard to find. In order to use data from real, designed and installed systems, the case studies were selected to include only buildings that were similar enough in form and function that any of the three HVAC systems considered could have been technically capable from a design perspective to meet equivalent demands in thermal comfort over an equivalent net area of office floor space.

5.3.4 Case study of HVAC systems: Data collection and analysis

A short list was compiled of types of HVAC systems that might be described as typical or particularly common in new build or fit-out projects for UK offices. According to a recent BRE study of energy use in air-conditioning systems by non-domestic buildings (Abela et al, 2016), the three most common types of system in a sample of 99 office buildings in the UK were single or multi-split systems followed by fan coil unit systems and single-duct variable air volume (VAV) systems. The FCU and VAV systems are generally used in medium to large offices, a point reflected by the fact that 70% of the office buildings surveyed had over 1000m^2 of cooled floor area. The category of 'single and multi-split systems' includes local direct exchange (DX) systems found in smaller buildings as well as variable refrigerant flow (VRF) systems found in medium to large buildings, as VRF systems are a form of multi-split system. This suggests that VRF, VAV and FCU systems are all potential candidates for case studies of office buildings with over 1000 m^2 of cooled floor space. They have key technological differences in terms of their levels of centralisation and the type and amount of distribution pipework or ductwork needed to transfer heat or cooling around a building, all of which impacts upon their embodied carbon.

A search was conducted using the sponsoring company's project database, supplemented by scoping interviews for current or recent office projects with accessible data on HVAC systems as designed or as installed. Information was reviewed from a number of projects featuring FCU, VRF, VAV and chilled beam systems. Of these, four projects were selected for which the range of available data met the quality standards for life cycle inventory data described earlier and would support a comparison of embodied impacts. Input parameters and data sources used for the case study of HVAC systems are summarised in Table 5.4. Further details of individual raw materials and EC coefficients for the composite HVAC components listed in this table are provided in Appendix 4.

Table 5-4: Input parameters and data sources used for case study of HVAC systems

Component and raw material(s)	Buildings in which used	Mass of component	Embodied carbon coefficient (ECC)	Source of data
Air-cooled chiller with centrifugal compressor, 2 No * 400kW capacity - various raw materials (VRM)	1	5,660 kg	2.3 kg CO_2 e / kg	Mass from contractor's schedule of installed equipment, bill of materials (BOM) estimated based on Riviere et al, 2012b, p62. ECCs from Hammond & Jones (H&J), 2011.
Air-cooled chiller with centrifugal compressor, 7760 kW capacity, VRM	4	32,428 kg	2.3 kg CO_2 e / kg	Mass from contractor's schedule of installed equipment, bill of materials (BOM) estimated based on. ECCs from Hammond & Jones (H&J), 2011.
Air handling units - various sizes, VRM	1,2,3,4	Various masses	2.21 kg CO_2 e / kg	Mass from contractor's schedule of installed equipment, BOM estimated based on Heikkila (2008), ECCs from H&J (2011).
Attenuators - galvanised sheet steel, UK/EU recycled proportion of 59%	1,4	Various masses	1.54 kg CO_2 e / kg	Size and quantity of units from 'as built' design drawings, mass & density from product literature, ECC from H&J, 2011
Condenser boiler, 750 kW, VRM	1	611 kg	1.97 kg CO_2 e / kg	Mass from contractor's schedule of installed equipment, BOM estimated based on Kemna et al, 2007. ECCs from H&J, 2011
Ductwork - galvanised sheet steel, UK/EU recycled proportion of 59%	1,2,3,4	Various masses (1)	1.54 kg CO_2 e / kg	Size and quantity from 'as built' design drawings, mass & density from industry standard (BESA, 2013), ECC from H&J, 2011
Fan coil units (FCUs), various sizes and VRM	1	Various masses	2.75 - 2.91 kg CO_2 e / kg (Average = 2.87 kg CO_2 e / kg)	Raw materials from manufacturers' BOM and tear-down analysis, ECCs sourced as outlined in Table 5.3 earlier
Linear diffusers - general aluminium, UK typical value	1	2.7-5 kg /linear metre	9.16 kg CO_2 e / kg	Size and quantity from 'as built' design drawings, mass & density from product literature, ECC from H&J, 2011
Pipework - carbon steel	1	1.3-4 kg /linear metre	2.02 kg CO_2 e / kg	Size and quantity from 'as built' design drawings, mass & density from product literature, ECC from Ecoinvent v 3.1, 2014
Pipework - copper - tube and sheet, UK/EU recycled proportion of 37%	2,3,4	0.5-2 kg /linear metre	2.71 kg CO_2 e / kg	Mass & density from product literature, ECC from H&J, 2011
Swirl diffusers, 81% general aluminium, 19% general plastic	2	11.2 kg per unit	5.78 kg CO_2 e / kg	BOM from product literature, ECCs from H&J, 2011
Fan assisted VAV terminal unit, various sizes and VRM	4	Various masses	1.74 kg CO_2 e / kg	Raw materials from tear-down analysis, ECCs from H&J, 2011
VRF indoor terminal unit, various sizes and VRM	2,3	23 kg per unit	2.75 kg CO_2 e / kg	Estimated based on BOM for FCUs of similar size, ECC from H&J, 2011
VRF rooftop condenser unit, various sizes and VRM	2,3	320-490 kg per unit	2.9 kg CO_2 e / kg	Estimated based on BOM for FCUs of similar size, ECC from H&J, 2011

5.4 Findings

This section presents the results of the life cycle impact assessments of the case studies of fan coil units and HVAC systems.

5.4.1 Embodied carbon impacts of fan coil unit range

The average raw material content and product-stage embodied carbon impact of a range of fan coil units produced by UK-based manufacturer 'A' are shown in Figures 5.6 and 5.7. The data is taken from manufacturer's bills of materials (BOM) of a range of FCU models going from 2-8 kW in total cooling capacity. As is discussed later, an experimental tear-down study of an FCU from the same range was also carried out to check the reliability of the data on mass from the BOM.

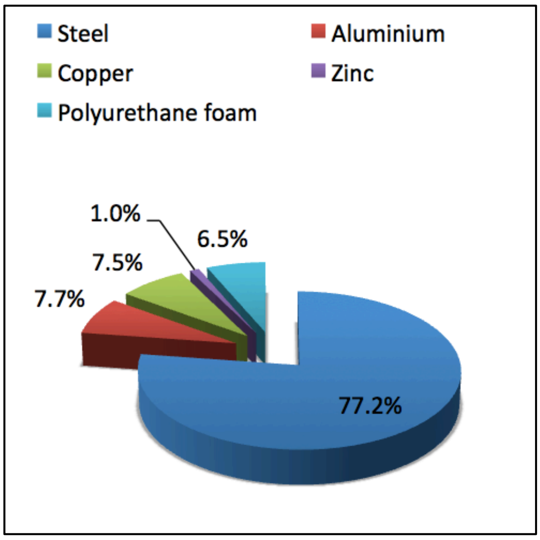

Figure 5-6: FCU Average material content

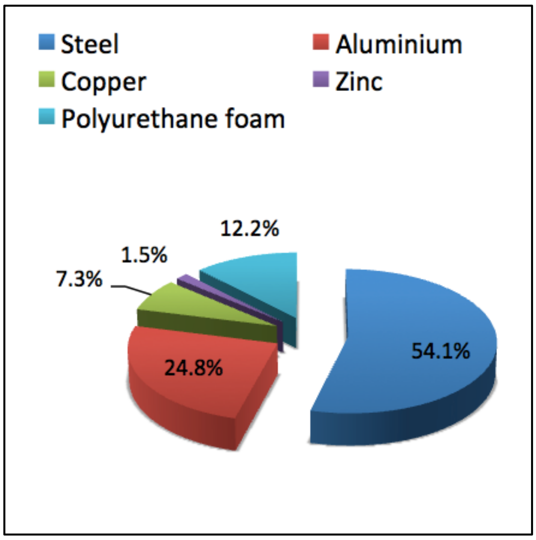

Figure 5-7: FCU average embodied carbon content

Differences between carbon intensities of materials mean that steel make up just over half of embodied carbon although it represents nearly 80% of mass, while the relative share of aluminium in embodied carbon is over three times its share in mass. Total embodied carbon of the FCU is 198 kg CO_2 e for a total mass of 69 kg, giving an average embodied carbon coefficient of 2.89 kg CO_2 e/kg. Raw material impacts are responsible for 96% of embodied carbon, with production energy and transport making up the rest. Of the raw material impacts, a significant proportion, 12.6%, are from the production of scrap steel and polyurethane (PUR) foam generated in manufacturing the FCU's outer casing. The scrap amounts to an extra 30% of galvanised steel mass and an extra 10% of PUR foam mass.

The next factor to consider is how mass, material content and embodied carbon change across the available range of FCUs in terms of size and power. Material content is relatively consistent with the steel proportion falling only from 79.8% to 76.5% between the bottom and top of the range, as shown in Figure 5.8. Mass and embodied carbon both rise with total cooling capacity, although the rise happens in uneven increments, as shown in Figure 5.9. The uneven increments are associated with sub-components being resized at different points along the range, as shown in Figure 5.10. For example, the main sub components of the FCU by mass are the steel casing, the fan-motor assemblies and the heat exchanger coils. While the steel casing for models 2 and 3 has identical size and mass, the fan-motor assembly of model 3 has twice the mass of that of model 2 because it has twice as many fans.

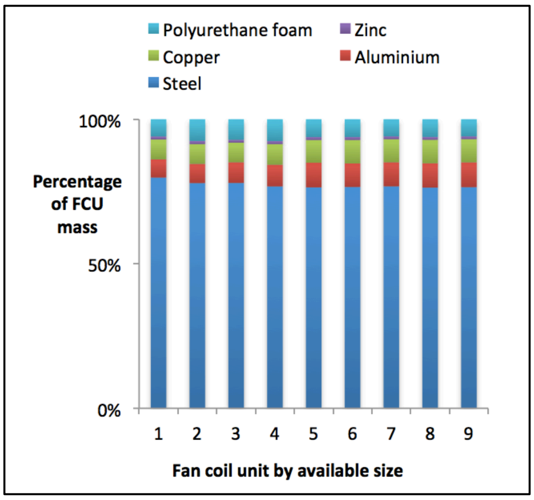

Figure 5-8: FCU range by material content

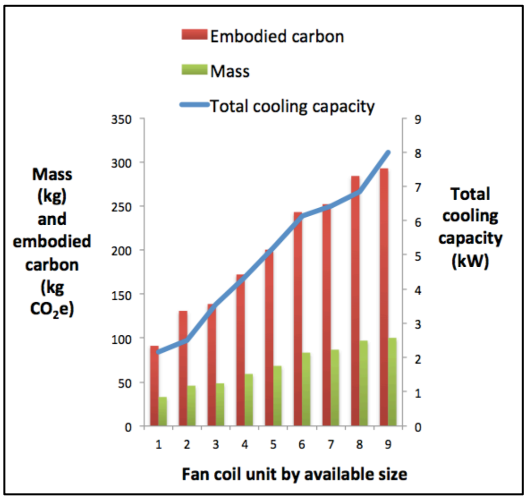

Figure 5-9: FCU range by mass, embodied carbon and total cooling capacity

Mass and embodied carbon relative to total cooling capacity of each FCU both fall as FCU size and power increase, as shown in Figure 5.11, except for a spike at the second unit in the range, which can be seen from Fig 5.10 to match an increase in casing mass that exceeds the increase in total cooling capacity between models 1 and 2.

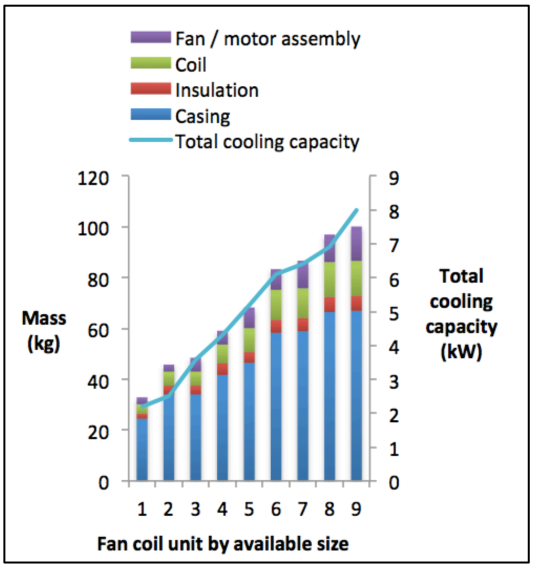

Figure 5-10: FCU range by mass, sub-component and total cooling capacity

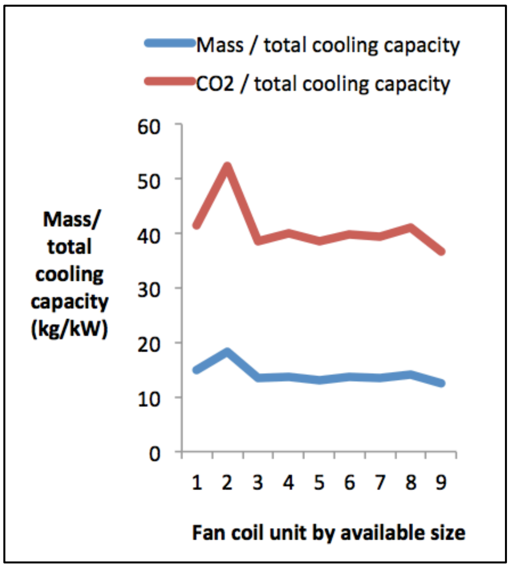

Figure 5-11: FCU range by mass and embodied carbon relative to total cooling capacity

These results indicate that despite the relative consistency of proportions of different materials across the size and power range of FCUs, (b) embodied carbon (EC) and mass vary directly with total cooling capacity (TCC); and (c) relative EC and mass fall slightly as TCC rises but are sensitive to spikes in unit mass. This raises the possibility that TCC could be used as a metric to multiply the EC values of a base FCU to generate estimated values for an FCU of any particular size. The main challenge to doing this is that the relationship between EC as the dependent variable and TCC as the independent variable is not linear. The EC of a base model of the component cannot easily be multiplied by the metric 'power output' to predict the EC of a model with other levels of rated power, as was proposed by a previous study (Moncaster and Symons, 2013). Also, the ratio of EC to mass of each FCU, which depends directly on the relative proportions of each raw material used to make it, varies less across the power range of FCUs than the ratio of EC to TCC.

This can be seen by a comparison of values for the dimensionless coefficient of variation (CV), which is defined in Equation 5.4 as the standard deviation, σ, of a random variable divided by its mean value, μ.

$$CV(x) = \frac{\sigma(x)}{\mu(x)} \qquad \text{(Equation 5.4)}$$

The CV of the ratio of EC to mass across the range of FCUs is 2.8%, whereas the CV of the ratio of EC to TCC is 9% and that of mass to TCC is 9.4%. This suggests that total mass may be a better metric for predicting EC value than TCC if internal proportions between raw materials are constant, as was the case with the FCU. However TCC values are also important as they explain why a component of a particular total mass is produced. To explore this further, the predictive value of both mass and TCC are considered in the next section.

5.4.2 Comparison of EC impacts by manufacturer and rated power

To investigate the effectiveness of using TCC and/or mass to predict embodied carbon, the known total masses of operationally equivalent FCUs produced by five manufacturers were compared across the available sizing range of each FCU as defined by its TCC. The functional unit for the comparison of EC was 'the product stage GWP impact of a ducted, water side FCU of TCC varying from 2 to 8 kW'. All five manufacturers' ranges were confirmed from product literature to use the same main raw materials and were produced in the UK. Based on this, internal raw material proportions and EC intensities per material for FCUs B-E were assumed equal to average values derived from bills of materials for FCU 'A'. Therefore variations between manufacturers in total mass of FCUs with a similar cooling capacity might indicate differences in embodied carbon efficiency between manufacturers. Figures 5.12 and 5.13 respectively plot mass against total cooling capacity and relative mass per kW of all five FCU ranges.

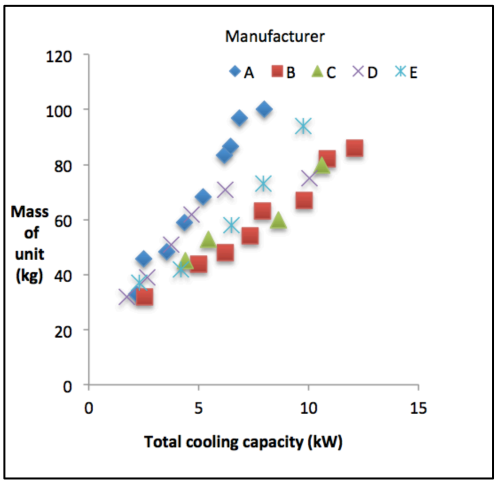

Figure 5-12: Mass of FCU range vs. total cooling capacity by manufacturer

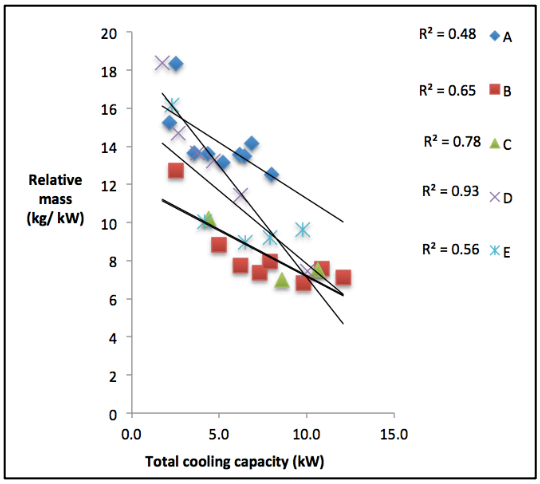

Figure 5-13: Mass relative to total cooling capacity of FCUs by manufacturer

The comparison shows firstly that FCU mass varies directly with total cooling capacity for all manufacturers as might be expected, while the rate of variation, or slope, shown in Figure 5.12, differs significantly between manufacturers. The vertical distance between coordinates in series A and B at each level of total cooling capacity shows that FCU A requires between 1.43 and 1.54 as much mass as FCU B to deliver a similar amount of cooling power. Secondly, the comparison confirms that relative mass of FCUs tends to fall as total cooling capacity rises, as indicated by the downward regression lines in Figure 5.13. This suggests that larger FCU models have a greater power to weight ratio, although it should be noted that the trend varies in strength as shown by a value of the coefficient of determination, r^2 of between 0.47 and 0.93. Without including uncertainty analysis of input parameters in a calculation model, to what extent might embodied carbon therefore be predicted deterministically based on benchmarks for total mass and internal material composition of FCUs of given cooling capacity? One way to do so is to reduce uncertainty by explaining variations in mass and ratios of mass to cooling capacity between manufacturers. Possible explanations for these variations could include the use of materials of varying density to make similar components and differences in dimensions of the steel casing impacting on the total mass of the unit.

Subject to the limitations mentioned above on availability of primary data from every manufacturer and the assumption of consistency between main raw materials used by manufacturer A and the others four, these issues can be explored using a simple sensitivity analysis.

5.4.3 Sensitivity of results to variations in mass

If it is assumed that galvanised steel casing makes up the majority of FCU mass and that UK-produced galvanised steel is of standard density, it follows that differences in the thickness of the casing used will substantially affect FCU mass. Product literature indicates that manufacturers A and C use 1.2mm gauge steel while manufacturer E uses 1mm gauge steel for the casing. Typical densities for UK-made galvanised steel are 9.083 kg/m^2 for 1.2mm gauge steel and 7.888 kg/m^2 for 2mm gauge steel (Custompart, 2018). Assuming that the FCU casing represents 70% of the mass of an average model, as it did across the range of models measured, then manufacturer E's models should have 1-(0.7-(7.888/9.083*0.7)) = 9.08% less mass than those of manufacturer A. The effect of reducing the mass of FCU 'A' by 9.08% would shift its mass/power curve closer towards the curve of unit E as currently visualised in Figure 5.9a. This would explain 30% of the difference in mass between manufacturers A and E at each level of total cooling capacity. While this cannot explain the observed difference in unit mass between manufacturers A and C, as they both use 1.2mm gauge galvanised steel, it shows the importance of material density in explaining variations in mass.

5.4.4 Review of deterministic EC estimation

Clearly, variations in mass between FCUs by manufacturer cannot all be explained away in order to reduce uncertainty to zero, although this does not necessarily make deterministic embodied carbon estimation ineffective. If the main raw materials and technology are consistent across the product type, a comparison of the mass and total cooling capacity of FCUs made by a representative sample of manufacturers might be used to provide an average embodied carbon benchmark based on these two parameters. This would mean treating both mass and TCC as independent variables for the purposes of predicting EC as dependent variable, without attempting to specify a function to define the relationship between variables.

The drawback of this approach is that it does not quantify the uncertainty represented by the dispersion of values of EC between manufacturers. If, however, the variations in mass between manufacturers for FCUs of the same cooling capacity are used in uncertainty propagation, a measure of uncertainty for estimated EC can be obtained. Based on the data for the five FCU ranges, there is one point in the product ranges of three of the manufacturers, (specifically, manufacturers A, B and D in Figure 5.12 and 5.13) at which equivalent models exist with the same total cooling capacity. The mean and standard deviation of the total mass of each of the three models can therefore be used as input parameters for uncertainty analysis.

The effectiveness of embodied carbon estimation based on knowledge of mass and rated power of a composite component is also influenced by the extent of variation between either (a) designed versus installed or (b) estimated versus measured values for the mass of that component. The previous section illustrates the first of these points. A building services design specification might require a fan coil unit of 2.5 kW total cooling capacity, but the choice of models installed to meet that specification could be met by any of the three manufacturers A, B or D in Figures 5.12-5.13. The procurement decision might typically be made by a contractor after the design was complete. As the usefulness of embodied carbon estimation to building services designers depends on predicting the impact of a component before the component is selected and installed, a deterministic estimation method would not resolve the uncertainty over the final choice of component.

On the second point (b), an experimental tear-down analysis of a fan coil unit produced by manufacturer 'A' produced a measured mass that was 6.3% greater than the value recorded by the manufacturer's bill of materials. Knowledge of such percentages can help estimate the uncertainty of values for component mass quoted by manufacturers of composite components in their product literature even when a complete bill of materials is not available. Both cases represent practical reasons why variations in the mass of a composite HVAC component should be modeled using uncertainty analysis as part of the process of estimating embodied carbon for that product.

5.4.5 Findings on parameter uncertainty

This section presents the results of applying uncertainty analysis to existing data on fan coil units and additional data on HVAC systems at building level.

5.4.5.1 Uncertainty of mass of fan coil unit A

The first result concerns uncertainty about the value of the mass of FCU A, m. If it assumed initially that the carbon coefficients k_R, k_T and k_{MF} are fixed and not uncertain, then the uncertainty of embodied carbon associated with uncertainty in raw material mass is given by term U_m in Equation 5.5.

$$\mathrm{EC}_{cc} = \sum_{i=1}^{n}[mk_R] + \sum_{i=1}^{n}[mk_T] + \sum_{i=1}^{n}[mk_{MF}] \pm U_m$$

(Equation 5.5)

In equation 5.5, the error term U_m represents two standard deviations about the estimated value of embodied carbon EC_{cc}, which in turn is defined as the sum of products of material masses m and embodied carbon coefficients for raw material extraction k_R, transport k_T and manufacturing k_{MF}. It is also assumed that input uncertainty for the masses of each of the five main raw materials used to construct a fan coil unit is set by a coefficient of variation (CV) of 10% and there is no covariance between materials. Following application of uncertainty propagation by either AUP or MCS, with AUP used to calculate the contribution to variance in both cases, the value of U_m will have a CV of approximately 6% across the FCU range. The effect on estimated embodied carbon is illustrated in Figure 10 by the error bars representing a distance of ± two standard deviations from the estimated value of embodied carbon, with the values for output uncertainty obtained by each method shown in Table 5.5.

Table 5-5: Comparative results of uncertainty propagation on mass of FCU A

Results with symmetrical triangular probability distribution for mass *m*									
FCU No.	1	2	3	4	5	6	7	8	9
Mean EC *kg CO_2e*	90.59	130.03	137.71	170.95	198.94	241.37	250.34	282.10	290.73
SD (MCS)	5.39	7.72	8.12	10.13	11.79	14.22	14.69	16.50	17.26
SD (AUP)	5.36	7.70	8.15	10.12	11.78	14.29	14.82	16.70	17.21
CV (MCS)	5.94%	5.93%	5.89%	5.94%	5.93%	5.88%	5.88%	5.83%	5.95%
CV (AUP)	5.92%	5.92%	5.92%	5.92%	5.92%	5.92%	5.92%	5.92%	5.92%
Results with normal (Gaussian) probability distribution for mass *m*									
SD (MCS)	5.37	7.64	8.16	10.20	11.68	14.23	14.88	16.81	17.41
SD (AUP)	5.36	7.70	8.15	10.12	11.78	14.29	14.82	16.70	17.21
CV (MCS)	5.93%	5.88%	5.90%	5.97%	5.88%	5.89%	5.93%	5.95%	6.00%
CV (AUP)	5.92%	5.92%	5.92%	5.92%	5.92%	5.92%	5.92%	5.92%	5.92%

In Table 5.6, the standard deviation (SD) and coefficient of variation (CV) for the estimated mean value of embodied carbon (EC) obtained by MCS with 10,000 simulation runs are compared with those obtained by AUP for a range of nine fan coil units of varying cooling capacity. Differences between results obtained by each method are not significant. The average difference between the dimensionless CV obtained by AUP and MCS for FCUs 1-9 is 0.06% when a triangular probability distribution is used and 0.09% when a normal distribution is used.

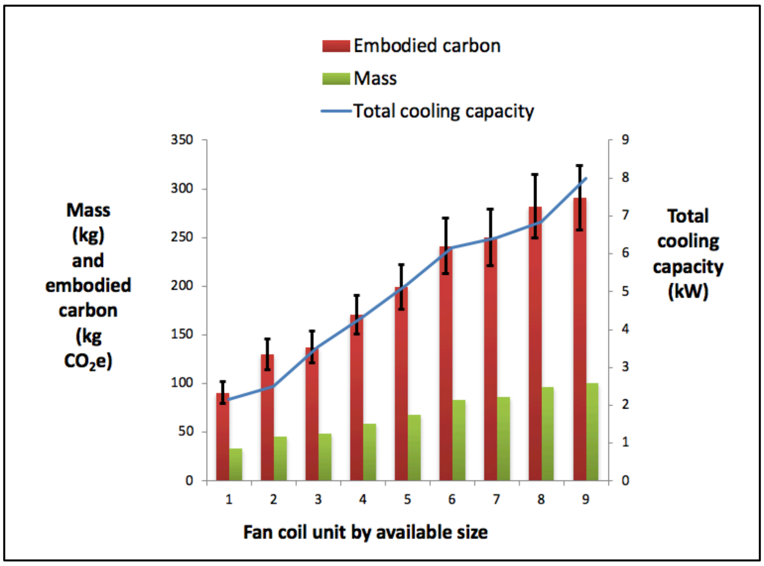

Figure 5-14: FCU range by mass, EC and total cooling capacity with uncertain mass

The significance of the result for practical estimation of embodied carbon is assessed by discernibility analysis. Wherever the error bars show in Figure 5.14 for any two FCU models overlap vertically, the estimated embodied carbon of each model can be described as not significantly different. This is because if the result were obtained by MCS using a normal (Gaussian) probability distribution for the input parameter *m*, the estimated value plus or minus two standard deviations would be equivalent to a confidence interval of 95.5%. The error bars shown on Figure 5.14 do not overlap between FCU models 1 and 2, indicating that the estimated EC values of these two models can be described as significantly different. For all other comparisons between FCU models across the size range, error bars overlap between at least two adjacent models and in the case of models 6-9, between four adjacent models. For these comparisons the estimated EC values cannot be described as significantly different.

5.4.5.2 Comparison of uncertainty scenarios for fan coil units

The results of embodied carbon estimation under uncertainty are now considered across three scenarios in which one or more of the four input parameters, m, k_R, k_T and k_{MF} may be uncertain. The scenarios are applied firstly to a model in the FCU A range with cooling capacity of 2.5 kW and then to a comparison of FCUs made by manufacturers A, B and C with the same cooling capacity but different mass, with the last comparison including an assessment of the relative significance of embodied and operational carbon over a 10 year product lifespan. In each case, uncertainty propagation using AUP is tested against MCS using 10,000 simulation runs. As the impacts of transport and energy used in manufacturing were found empirically form the data provided by manufacturers to represent only 4% of total embodied carbon of a fan coil unit, the value used for k_R includes the effects of k_T and k_{MF}. The parameters for which uncertainty is varied are therefore designated m for mass and k_R for the combined product stage carbon coefficient. The scenarios are as follows:

- Scenario 1: For copper, aluminium, polyurethane foam and general steel, m has uncertainty indicated by a coefficient of variation (CV) of 10%, the CV for galvanised steel mass is 5% and k_R has no uncertainty.
- Scenario 2: CVs for m for all materials are 10% and k_R has no uncertainty.
- Scenario 3: CVs for both m and k_R are all set at 10%, except for copper, for which the CV for m is 10% but k_R has no uncertainty.

Application of the three scenarios to the FCU model using either method of uncertainty propagation shows that the effect of uncertainty of each scenario is influenced not only by the relative uncertainty of each input parameter, but also by the sensitivity of embodied carbon to both the relative shares of each raw material in FCU mass and the relative carbon intensity of each raw material. Although galvanised steel is the least carbon intensive material, it makes up 74% of the mass of the FCU, so doubling of the uncertainty of galvanised steel raises total variance of embodied carbon by a multiple of 2.5 and raises the contribution to variance (CTV) of galvanised steel from 51% to 81%. This can be seen by a comparison of scenarios 1 and 2 in Figures 5.15 (a) and (b). Conversely, aluminium makes up only 7% of FCU mass but is the most carbon intensive material, so its CTV is between 13% and 32%, as shown in Figure 5.15 (b).

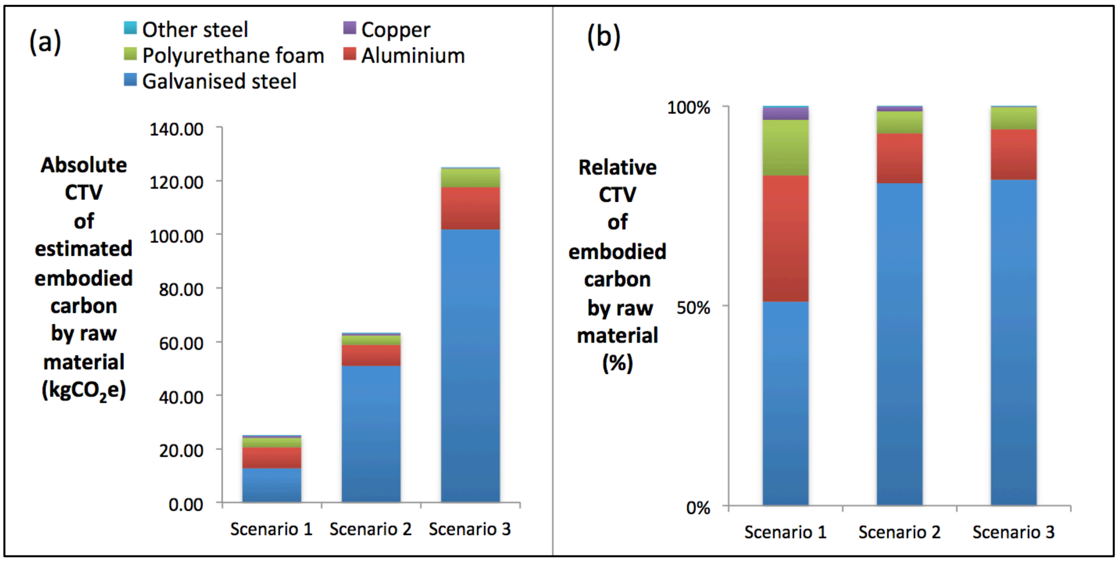

Figure 5-15: Contribution to variance of embodied carbon under 3 scenarios for FCU A

As in the previous test, the estimated uncertainty for FCU A using the AUP and MCS methods does not differ significantly, with the CV obtained by AUP on average within 0.2% of that obtained by MCS using either a triangular or a Gaussian distribution. This is shown in Table 5.7. The results show that the AUP method can estimate the effects of varying levels of input parameter uncertainty on embodied carbon output with minimal calculations when combined with information on sensitivity of output to input parameters. The next question to examine is how this method might be combined with information on operational carbon emissions to identify whether carbon impacts of alternative but equivalent components are substantially different over a product lifetime.

5.4.5.3 Comparison of fan coil units by manufacturer and scenario

In this case, three FCUs of varying mass and operational energy efficiency but similar cooling capacity and raw material composition are compared in relation to their (a) product stage embodied carbon impacts under the three uncertainty scenarios and (b) operational carbon impacts over 10 years, estimated deterministically but reflecting their differences in operational energy consumption. The functional unit used for comparison here is 'the product stage and operational GWP impacts of a single FCU, sized to meet a notional, maximum office cooling load of 2.5 kW for the equivalent of 25% out of 12 hours daily use over a 10 year period'. Table 5.6 provides further details of the parameters used.

Table 5-6: Input parameters for comparison of EC and OC by manufacturer

Parameter	Component		
	FCU A	FCU B	FCU C
Total mass (kg)	45.8	32	39
Proportions of raw materials assumed to equal those measured from bill of materials for FCU A: Galvanised steel – 74.37%, PUR foam – 7.49%, copper – 6.86%, aluminium - 6.63%, general steel - 4.65%. An extra 30% of galvanised steel mass and 10% of PUR foam mass from scrap generated in manufacturing is included in the calculation of embodied carbon	As stated in column 1	As stated in column 1	As stated in column 1
Mean embodied carbon, estimated using EC coefficients from Table 5.3 - kg CO_2e	130.03	90.90	110.78
Specific fan power - Watts/litres/sec	0.3	0.31	0.46
Total cooling capacity - kW	2.5	2.5	2.5
Fan motor type	EC/DC	EC/DC	AC
Maximum input power - Watts	45	49	105
Operational energy (OE) use over 10 years (kWh) *assuming notional energy consumption (kWh) = input power (Watts)*12 hours*365.25 days* 0.25(utilisation rate)*10 years* 0.001 (conversion factor)*	493.09	536.92	1,150.54
Carbon intensity of UK grid electricity (CIG) in 2016 (kg CO_2/kWh) (BEIS, 2017, p123)	0.254	0.254	0.254
Operational carbon emissions over 10 years in kg CO_2e = (OE * CIG)	125.2	136.4	292.2

The results indicate firstly that for the most operationally energy efficient product, FCU A, mean embodied carbon (EC) is 2% greater than estimated operational carbon (OC) over a 10 year period, as shown in Figure 5.16. Also, FCU A has an OC value 8% lower than that of FCU B but its mean EC is 40% greater, making its combined (EC+OC) emissions 12% higher. Under scenario 1, the uncertainty is of each estimate is small enough for the estimated EC+OC impacts of FCUs A, B and C to each be significantly different, as shown by the error bars Figure 5.16 not overlapping between any two of the three FCUs. However, under scenarios 2 and 3, the error bars of FCUs A and B overlap, indicating that these estimates for EC+OC impact are *not* significantly different. If the estimated OC emissions of all three FCUs were also modelled to include uncertainty and this were to increase total uncertainty by 40%, the error bars in Figure 5.16 for FCUs

A and B under scenario 1 would also overlap, therefore estimated EC+OC of FCUs A and B under all three scenarios would not now be significantly different.

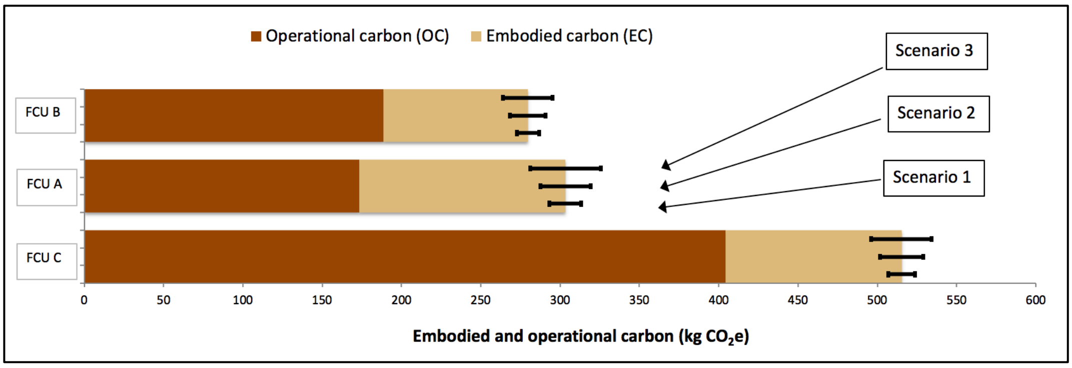

Figure 5-16: Comparison of EC and OC of three FCUs with uncertainty

The results of uncertainty analysis by AUP and MCS using alternate types of probability distribution with respect to embodied carbon are shown in Table 5.7.

Table 5-7: Comparative results of uncertainty propagation on equivalent fan coil units

Results with symmetrical triangular probability distribution for mass and EC coefficient k_R									
FCU	A			B			C		
Scenario	1	2	3	4	5	6	7	8	9
Mean EC *kg CO_2e*	130.03	130.03	130.03	90.90	90.90	90.90	110.78	110.78	110.78
SD (MCS)	5.02	7.84	11.33	3.51	5.58	7.88	4.24	6.77	9.58
SD (AUP)	4.99	7.94	11.17	3.49	5.55	7.81	4.25	6.76	9.51
CV (MCS)	3.86%	6.03%	8.72%	3.86%	6.13%	8.66%	3.83%	6.11%	8.64%
CV (AUP)	3.84%	6.11%	8.59%	3.84%	6.11%	8.59%	3.84%	6.11%	8.59%
Results with normal (Gaussian) probability distribution for mass and carbon coefficient k_R									
SD (MCS)	5.01	8.05	11.26	3.48	5.55	7.79	4.28	6.82	9.68
SD (AUP)	4.99	7.94	11.17	3.49	5.55	7.81	4.25	6.76	9.51
CV (MCS)	3.85%	6.18%	8.66%	3.83%	6.11%	8.57%	3.87%	6.16%	8.73%
CV (AUP)	3.84%	6.11%	8.59%	3.84%	6.11%	8.59%	3.84%	6.11%	8.59%

A comparison of the respective standard deviations (SD) and coefficients of variation (CV) obtained by AUP and MCS in Table 5.7 shows that differences between results of uncertainty propagation using each method are minimal. The average difference between the dimensionless CV obtained by the AUP and MCS methods across all three scenarios for all three FCUs is 0.35% for the triangular distribution and 0.58% for the normal distribution.

5.4.5.4 Comparison of embodied carbon impacts of HVAC systems

The comparison of embodied carbon impacts of HVAC systems builds on the case studies of fan coil units by using a combination of estimation and measurement methods to consider the relative embodied impacts per m^2 of net internal building floor area for each system. As shown in Tables 5.2 and 5.5, this includes data from experimental measurements of component mass, manufacturers bills of materials, design drawings, BIM models and published environmental product declarations (EPDs). Each generic component and each carbon coefficient is allocated an equivalent input uncertainty distribution with a coefficient of variation (CV) of 10% and uncertainty propagation is tested using MCS against AUP for scenarios with either a triangular or normal probability distribution for input uncertainty. The key features of the four HVAC systems are summarised in Table 5.8 and the results of the comparison are illustrated in Figure 5.17.

Table 5-8: Key features of four HVAC systems studied

Building	Net internal area (m^2)	HVAC system type
Building 1	3,863	Partially centralised, fan coil unit (FCU)
Building 2	4,323	Locally distributed, variable refrigerant flow (VRF)
Building 3	3,815	Locally distributed, variable refrigerant flow (VRF)
Building 4	44,593	Centralised, variable air volume (VAV)

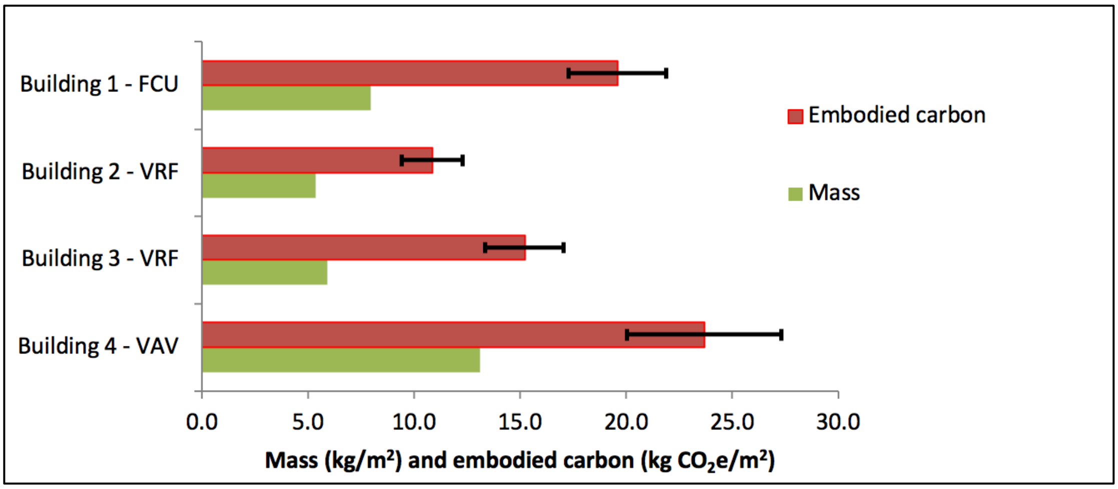

Figure 5-17: Comparison of mass and embodied carbon of four HVAC systems with uncertainty

The comparison of HVAC systems by embodied impact shows firstly that mean embodied carbon per m^2 varies significantly by system type, with the mean value for the VAV system between 1.6 and 2.2 times greater than that of the two VRF systems and 1.2 times greater than that of the FCU system, as shown in Figure 5.13. The error bars show output uncertainty as calculated by the AUP method at $\pm$2 standard deviations away from mean output. The differences in mean EC values are the result of variations in the raw material type, total mass and carbon intensity of the set of components comprising each HVAC system.

A breakdown of embodied carbon by component and by HVAC system type, as illustrated in Figure 5.18, provides potentially important clues as to the reasons for these noticeable differences:

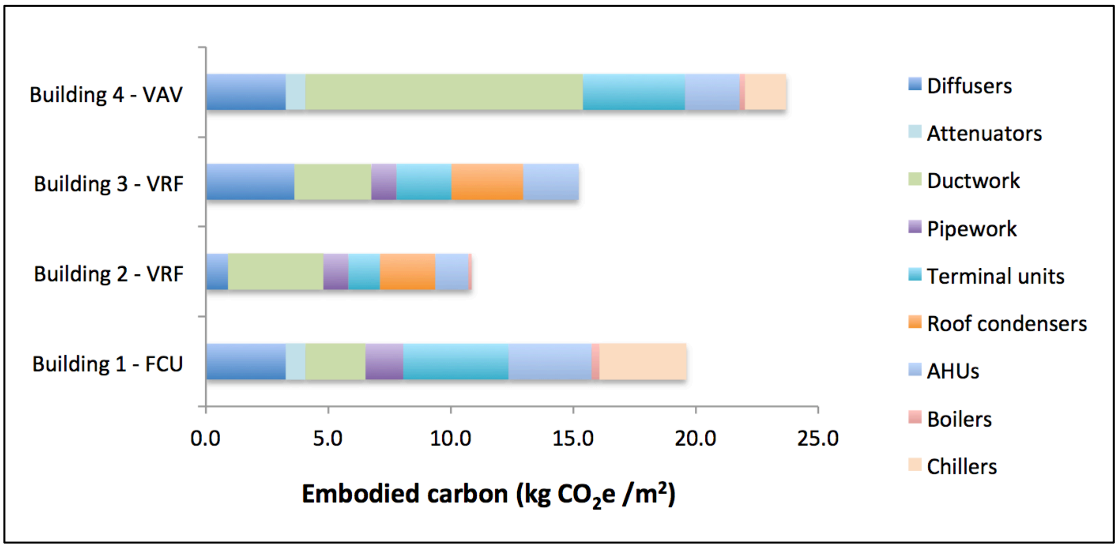

Figure 5-18: Comparison of embodied carbon of four HVAC systems by component

- The VAV system in building 4 uses an all-air distribution method rather than an air/water or refrigerant-based method, therefore it requires 2.9-4.6 times as much galvanised steel ductwork as the other systems.
- The reliance of the two partially centralised systems in buildings 1 and 4 on a central chiller or chillers means that chillers are responsible for between 7-18% of the embodied carbon of each HVAC system.
- Buildings 2 and 3 both have VRF systems with very similar components, but the embodied carbon impact of the system in building 3 is 40% greater partly because it uses diffusers made of aluminium and steel that are 3.4 times more carbon intensive than the steel and plastic diffusers used in building 2.
- The pipework used in building 1 has 1.5 times the embodied carbon impact of that used in buildings 2 and 3, even though it is made of carbon steel, which is 25% less carbon intensive than the copper pipework in buildings 2 and 3. This is because the 4-pipe fan coil system in building 1 uses twice as much mass in pipework per square metre of floor space as the 2-pipe systems used in buildings 2 and 3, due to technical differences between the ways that FCU and VRF systems are able to heat and cool different areas of a building simultaneously.

The effect of uncertainty analysis of the mass and carbon coefficients for generic components in each HVAC system indicates that the VAV systems has significantly different embodied carbon impacts then those of the two VRF systems, as shown by the non-overlapping error bars between Building 4 and Buildings 2 or 3 in Figure 5.17. This aligns with expectations based on technical differences between HVAC systems by type. Conversely, the overlapping error bars between the EC values for Buildings 1 and 4, and similarly those between buildings 1 and 3, indicate that in some cases alternative types of HVAC systems may not have significantly different EC impacts. It is also apparent from the non-overlapping error bars of the two VRF systems in Figure 5.17 that differences in EC values between two examples of the same HVAC system can be significant.

There is again only a minimal difference between the results obtained by the MCS and AUP methods as shown in Table 5.9. The average difference between the dimensionless CVs obtained by the AUP and MCS methods across the four building case studies is 0.3 % for the triangular distribution and 0.6 % for the normal distribution.

Table 5-9: Comparative results of uncertainty propagation on four HVAC systems

Results with triangular probability distribution for mass *m* and carbon coefficient k_R				
	Building 1 - FCU system	Building 2 - VRF system	Building 3 - VRF system	Building 4 - VAV system
Mean embodied carbon/m² NIA	19.61	10.85	15.22	23.70
SD (MCS)	1.16	0.72	0.93	1.83
SD (AUP)	1.15	0.71	0.92	1.82
CV (MCS)	5.92%	6.60%	6.10%	7.74%
CV (AUP)	5.88%	6.59%	6.07%	7.67%
Results with normal probability distribution for mass *m* and carbon coefficient k_R				
Mean embodied carbon/m² NIA	19.61	10.85	15.22	23.70
SD (MCS)	1.16	0.72	0.93	1.82
SD (AUP)	1.15	0.72	0.93	1.82
CV (MCS)	5.89%	6.57%	6.10%	7.67%
CV (AUP)	5.87%	6.59%	6.07%	7.67%

The fact that VRF systems in two buildings can have significantly different embodied carbon impacts per square metre raises another issue. The modelling of input uncertainty allows for variation in mass or carbon intensity by generic component, but it is not intended to explain variations in design between two VRF systems such as alternate choices of plastic or metal diffusers. Similarly, the embodied impact of the indoor terminal units of the VRF system in building 2 is 70% higher than that of the units in building 3 because units of similar cooling capacity are specified in building 3 to cool an internal area that is around 58% smaller per terminal unit. This may be because of differences in the proportions of cellular to open plan office space in the office floors of each building. These two points suggest that a meaningful embodied carbon estimation method for HVAC systems would need to combine uncertainty analysis with uncertainty reduction. This would entail the reduction of uncertainty by identifying and classifying certain design options for each HVAC system as alternative scenarios, followed by the use of uncertainty analysis to compare these scenarios.

Lastly, although this analysis is based on only one or two empirical case studies of each type of HVAC system, it illustrates two principles which could arguably be confirmed by further case studies. Firstly, variations in estimates of embodied carbon can be associated with technical differences between different types of HVAC system and/or different design of the same type of HVAC system. Secondly, uncertainty propagation of input parameters can determine whether the variations in embodied carbon are significant when alternative HVAC design are compared.

5.4.5.5 Worked example

This section demonstrates the calculations and assumptions used to arrive at the results for estimated embodied carbon and uncertainty of the HVAC system in 'Building 1' in the preceding section. The first task is to calculate the nominal value of embodied carbon (EC) for the seven main types of components used in the HVAC system. To do so, raw material types and masses are obtained from the data sources identified in Table 5.4. The EC coefficients for raw material production, transport and manufacturing are obtained from Table 5.3. For each raw material, EC for the product stage is then calculated using Equation 5.1.

$$\mathrm{EC}_{cc} = \sum_{i=1}^{n}[mk_R] + \sum_{i=1}^{n}[mk_T] + \sum_{i=1}^{n}[mk_{MF}] \qquad \text{(Equation 5.1)}$$

For instance, the total mass m of fan coil units (FCUs) used in Building 1 is 5,523 kg. This is made up of galvanised steel (70.94%), other steel (7.42%), copper (7.31%), aluminium (7.18%) and polyurethane foam (7.15%). Each raw material is then multiplied by its respective value of k_R (shown in Table 5.3), producing a total value for nominal EC from raw material production of 15,323 kg CO_2e and a value for k_R of 2.77 kg CO_2e per kg of mass. This calculation is then repeated to obtain the coefficients k_T and k_{MF} for transport and manufacturing.

- The average distance travelled by road to bring raw materials from UK suppliers to the FCU manufacturer (166.3 km), which was based on empirical data provided by manufacturer 'A', is multiplied by the transport emission factor from Table 5.3 (0.114 kg CO_2e/tonne km). The result is 18.9 kg CO_2e per tonne of mass transported, or a value for k_T of 0.0189 kg CO_2e per kg of mass. The total value of GWP from transport is therefore 0.0189* 5,523 = 104.4 kg CO_2e.
- Similarly, the electrical energy and natural gas used for manufacture of each FCU (0.19 kWh per kg of mass) is multiplied by the grid emission factor for the year of production in Table 5.3 (0.394 kg CO_2e per kWh). The result is a value for k_{MF} of 0.073 kg CO_2e per kg of mass and a total value of GWP from manufacturing of (0.073*5,523) = 403.16 kg CO_2e. The overall EC coefficient k for product stage impacts of the FCUs in Building 1 is therefore equal to (k_R + k_T + k_{MF}) = 2.87 kg CO_2e per kg of mass.

The fact that EC associated with transport and manufacturing makes up only 3.2% of product stage EC for the FCUs of 15830.52 kg CO_2e indicates that it can if required be excluded under the cut-off rule, as it represents the effect of less than 5% of the energy input for the module A1-A3 (BSI, 2014). While this rule was not applied for the FCUs as full empirical data on transport and manufacturing energy was available, it was used for other components listed in Table 5.4 for which similar data was unavailable. By repeating the calculations just performed for the other six types of components in Building 1, nominal values of EC are obtained in each case, along with values for the overall EC coefficient k, which are shown in Table 5.10.

Table 5-10: Nominal value of embodied carbon of HVAC system in Building 1

Component	Raw material	Total mass *m* for each component	Value of EC coefficient *k* for product stage	Total value of EC (kg CO_2e)	EC per unit of floor area (kg CO_2e/m^2 NIA)
Air-cooled chiller	Various	5,660.0	2.30	13,018.0	3.53
Air handling units	Various	5,653.0	2.21	12,493.13	3.39
Condenser boiler	Various	611.0	1.97	1,202.76	1.97
Ductwork and attenuators	Galvanised steel	6,848.70	1.54	10,547.0	3.25
Fan coil units	Various	5,523.17	2.87	15,830.52	4.30
Linear diffusers	Aluminium	1,315.70	9.16	3,942.20	3.27
Pipework	Carbon steel	2,804.62	2.02	5665.39	1.54

The next step is to propagate uncertainty in the input parameter values for mass m and the EC coefficient k. This is done with Equation 2.1.

$$Var[y] \approx \sum_{i=1}^{n} var[x_i] \left[\frac{\partial y}{\partial x}\right]_{X^0}^{2} \qquad \text{(Equation 2.1)}$$

To model the uncertainty of the input parameters, a measure of dispersion indicated by a coefficient of variation (CV) of 10% is assumed for each value of m associated with the total mass of each of the seven components. The estimated value of the CV acts as a proxy for several sources of uncertainty. Firstly, as discussed in section 5.4.4, a difference of 6.3% was recorded between the mass of a fan coil unit measured by on site tear-down analysis and that recorded in a manufacturer's bill of materials. Similar variations might also apply to other composite components such as chillers and air handling units. Secondly, it was pointed out by the mechanical services contractors for Building 1 that the final quantities of components installed may have varied slightly from those described in the 'installed' design drawings and schedules, which were used to take off quantities used in this study. Thirdly, the bills of materials assumed for the chillers and air handling units were based on secondary data from equivalent products as indicated in Table 5.4, therefore some uncertainty was associated with the internal raw material proportions for these components.

A CV of 10% is also assumed for the value of *k* associated with each component. This value is used a proxy for the measure of dispersion of EC coefficients obtained from the Inventory of Carbon and Energy (ICE), although as ICE does not provide uncertainty ranges for EC values (Richardson, 2017, p143), the value is illustrative only. The result of applying Equation 2.1 to each of the seven groups of components in Building 1 leads to a series of values for the variance of EC of each group, as shown in Table 5.11. The square root of the sum of variances is equal to the standard deviation of nominal total EC of all seven component groups.

Table 5-11: Variance and standard deviation of EC estimate for Building 1

Component	EC per unit of floor area (kg CO_2e/m^2 NIA)	Variance (kg CO_2e/m^2 NIA)
Air-cooled chiller	3.53	0.21
Air handling units	3.39	0.21
Condenser boiler	1.97	0.05
Ductwork and attenuators	3.25	0.23
Fan coil units	4.30	0.37
Linear diffusers	3.27	0.002
Pipework	1.54	0.25
All components	19.61	
Descriptive statistics for HVAC system in Building 1		
Total variance (kg CO_2e/m^2 NIA)		1.32
Standard deviation (kg CO_2e/m^2 NIA)		1.15
Coefficient of variation (%)		5.87

5.5 Interpretation of findings

This section considers the substantial issues arising from each stage of the LCA study in the context of the goal of the study, followed by an evaluation of the methods used.

5.5.1 Substantial issues

The most substantial issues arising from the results arise from the life cycle impact assessment are as follows:

- It is in principle possible to estimate embodied carbon based on input parameters for a composite HVAC component. In the case of fan coil units, this is possible if rated power, total mass and internal proportions between raw materials are known.

- When a generic class of composite components is identified by function and technology with consistent proportions of raw material inputs over its size and rated power range, there will still be design variations between UK-based manufacturers of this class of components. This makes deterministic embodied carbon estimation challenging unless uncertainty analysis is used for the impact assessment.
- The use of uncertainty analysis can determine whether significant differences exist between embodied carbon estimates for two composite components that differ by size and rated power, by manufacturer or by uncertainty scenario. Results obtained by the AUP method compare closely with those obtained by MCS and can in principle support comparisons of embodied and operational impacts of equivalent components by manufacturer.
- A comparison of the embodied carbon impact of equivalent HVAC systems for office buildings shows that differences in impacts can be associated with key technical differences between systems. However, significant differences can also exist between impacts of two designs of the same type of HVAC system due to variations in office layout or alternative choices of raw materials for equivalent components. In these cases uncertainty can be reduced by classifying the variations as alternative scenarios, whose embodied carbon impacts have been shown by uncertainty analysis to be significantly different.

5.5.2 Evaluation

An evaluation of the embodied carbon estimation method should fit within the context of the wider mitigation strategy for the threats to validity to this research. As the estimation method developed in this chapter is predominantly quantitative, the relevant types of validity to address are internal validity, external validity and reliability, as outlined in Table 3.4 of chapter 3. Within the

LCA standards, the checks on completeness, sensitivity and consistency are designed to address internal validity of a specific LCA study and these are therefore addressed in the next section.

Reliability, if defined as the applicability of a measurement method in one study across other studies, is addressed by the existence of general LCA standards on impact categories, and allocation and characterisation factors rather than the specific methods used in one study. External validity, in the sense of the applicability of the findings of an LCA study to another product, is not possible if individual studies adopt bespoke methods from within the available LCA standards. However the EPD standard and product category rules for construction products are designed to support comparisons between EPDs for products of the same type (BSI, 2014). The estimation method developed in this chapter is designed to support comparisons between generic HVAC systems or components and is therefore based on methods recommended by the ISO standards for LCA studies of buildings and of construction products (BSI, 2011, 2014).

5.5.2.1 Completeness check

The completeness check aims to verify that all information required by the goal and scope of the LCA study has been processed through the inventory and impact assessment stages and is available for interpretation (BSI, 2006b). For this study, there are three important caveats that apply to the completeness of the life cycle inventory analysis and the life cycle impact assessment.

The first caveat is that for the inventory analysis, detailed primary data for mass and energy inputs was obtained for the product range of fan coil unit A. However, data obtained for other UK manufacturers covered total mass, rated power and the type of the main raw materials but proportions of each material or amounts of energy used in transport and manufacturing, therefore these values were assumed to be proportionately equivalent to those measured for FCU A.

The second caveat is that inventory data used for other HVAC components also used a mixture of primary and secondary sources, as summarised in Tables 5.3 and 5.4. However, as all data used met the data quality requirements outlined above in section 5.2.3, variations in the depth of available inventory data should be seen as reflective of the real world context in which embodied carbon estimation of HVAC systems must currently be undertaken.

The third caveat is that in the uncertainty analysis, product stage GWP impacts were calculated and compared for the case studies and the effects of parameter uncertainty were explored using alternately normal and triangular probability distributions of inputs via the MCS and AUP methods. While this analysis met the scope of the study, the comparison could in principle have been repeated with an assumption of lognormal distributions for all uncertain inputs, as previous studies have suggested that this can be achieved using AUP (Hong et al, 2010).

5.5.2.2 Sensitivity check

The sensitivity check considers the extent to which the LCA results might be affected by variations in assumptions, methods or data (BSI, 2006b, p42). It is relevant here that the equations used for the AUP method (Equations 2.1 and 5.2) already incorporate the effects of both uncertainty and sensitivity of output, with sensitivity represented by the partial differential of output y with respect to input x_i. In other words, equation 5.2 also measures the 'uncertainty importance' of each input parameter, which means the relative contribution of uncertainty of a given input parameter towards total uncertainty of the result (Bjorklund, 2002). The uncertainty importance of embodied carbon of a single raw material relative to total EC of a composite component that includes that material depends both on the mass of the raw material and on the uncertainty of its mass and/or EC coefficient. The results illustrated in Figures 5.14-5.17 therefore reflect different scenarios in terms of both uncertainty and sensitivity. Considering sensitivity of the results at a wider level, the values for the embodied carbon coefficient for raw material supply, k_R, have mostly been drawn from the Inventory of Carbon and Energy (ICE), (Hammond and Jones, 2011). In order to examine the sensitivity of results to using a more recently updated LCI database, the comparison of four HVAC systems is repeated in Simapro 8 with Ecoinvent v3.1, which was issued in 2014, as the LCI database.

The results shown in Table 5.12 and Figure 5.19 indicate that mean embodied carbon per m^2 is between 8 - 36% lower when Ecoinvent is used. Variations are seen in the relative difference between embodied carbon between HVAC systems in different buildings according to the database used. Nominal EC of the VRF system in Building 3 exceeds that of a similar VRF system in Building 2 by 40% using the ICE database, but only by 15% using Ecoinvent. This happens because some materials appear much less carbon intensive than others when using a newer database and the proportions of each material used varies between HVAC systems. Uncertainty varies slightly when coefficients of variation (CV) associated with the Ecoinvent result are compared with those associated with the ICE result as seen in Table 5.10, with CVs on average 5% higher in buildings 1-3 and 10% lower in building 4. In contrast to the ICE result, the EC impacts of the two VRF systems in Buildings 2 and 3 are now *not* significantly different, as shown by the overlapping error bars in Figure 5.19. This is partly because the steel and aluminium diffusers used only in Building 3 are 74% less carbon intensive using data from Ecoinvent than their value based on ICE. Otherwise, the EC impacts of both VRF systems remain significantly different from those of either the FCU system or the VAV system, as was the case with the ICE result. The overall ranking of the four HVAC systems by EC impact also remains the same.

Table 5-12: Sensitivity of results to choice of life cycle inventory database

	Building 1 - FCU system	Building 2 - VRF system	Building 3 - VRF system	Building 4 - VAV system
Mean embodied carbon/m^2 NIA (ICE database)	19.61	10.85	15.22	23.69
Mean embodied carbon/m^2 NIA (Ecoinvent v3.1)	16.8	8.46	9.77	21.71
SD (AUP) - ICE	1.38	0.71	0.92	1.82
CV (AUP) -ICE	7.04%	6.59%	6.07%	7.67%
SD (AUP) - Ecoinvent	1.21	0.59	0.63	1.64
CV (AUP) - Ecoinvent	7.2%	7.0%	6.4%	7.6%

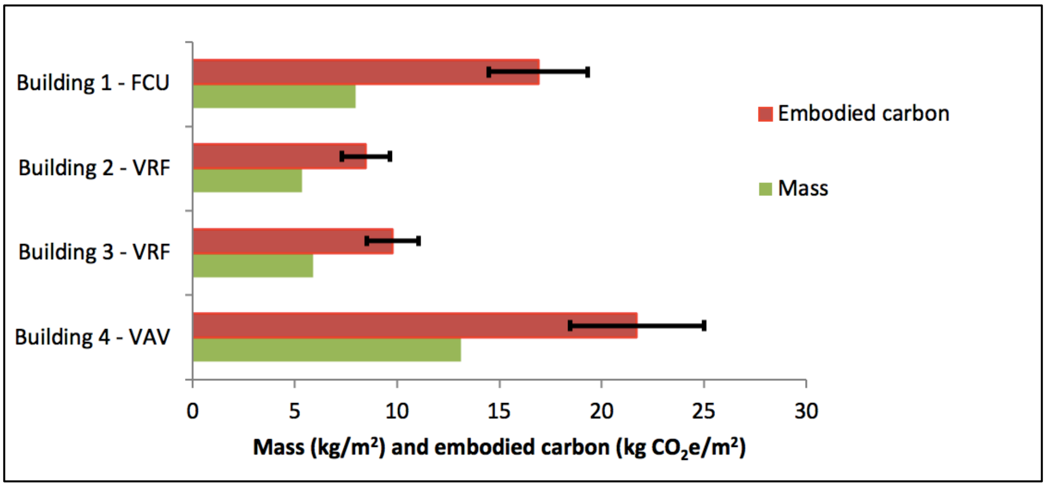

Figure 5-19: Comparison of mass and EC of four HVAC systems with uncertainty, using Ecoinvent

5.5.2.3 Consistency check

The consistency check is intended to verify the consistency of assumptions, methods, models and data used either across the life cycle of a product or between the options for which life cycle impacts are compared (BSI, 2006b, p44). In this study, the caveats already pinpointed and discussed in relation to completeness of the life cycle inventory data are equally applicable to the consistency of the data. This means that the main challenge to consistency in the use of a parametric method to estimate embodied carbon of HVAC components is that normative choices or assumptions must be made about life cycle inventory data if the data is incomplete before it can be processed via life cycle impact assessment. Typical examples of incomplete data include gaps in data about raw material proportions within a composite component or about the full probability distribution of an uncertain input parameter, whether it is a mass value, *m*, or a carbon coefficient, k_R, for the supply of a raw material. A practical solution to this challenge is to codify the steps taken in this chapter to apply the estimation method to inventory data with a decision-making schematic, which is shown in Figure 5.20. This diagram shows the specific process steps used in the study of fan coil units discussed in this chapter. However, a more generalised process model is later developed in chapter 8 and illustrated in Figure 8.2 to describe an iterative process by which uncertainty analysis and uncertainty reduction can be combined to develop the embodied carbon estimation method of this study.

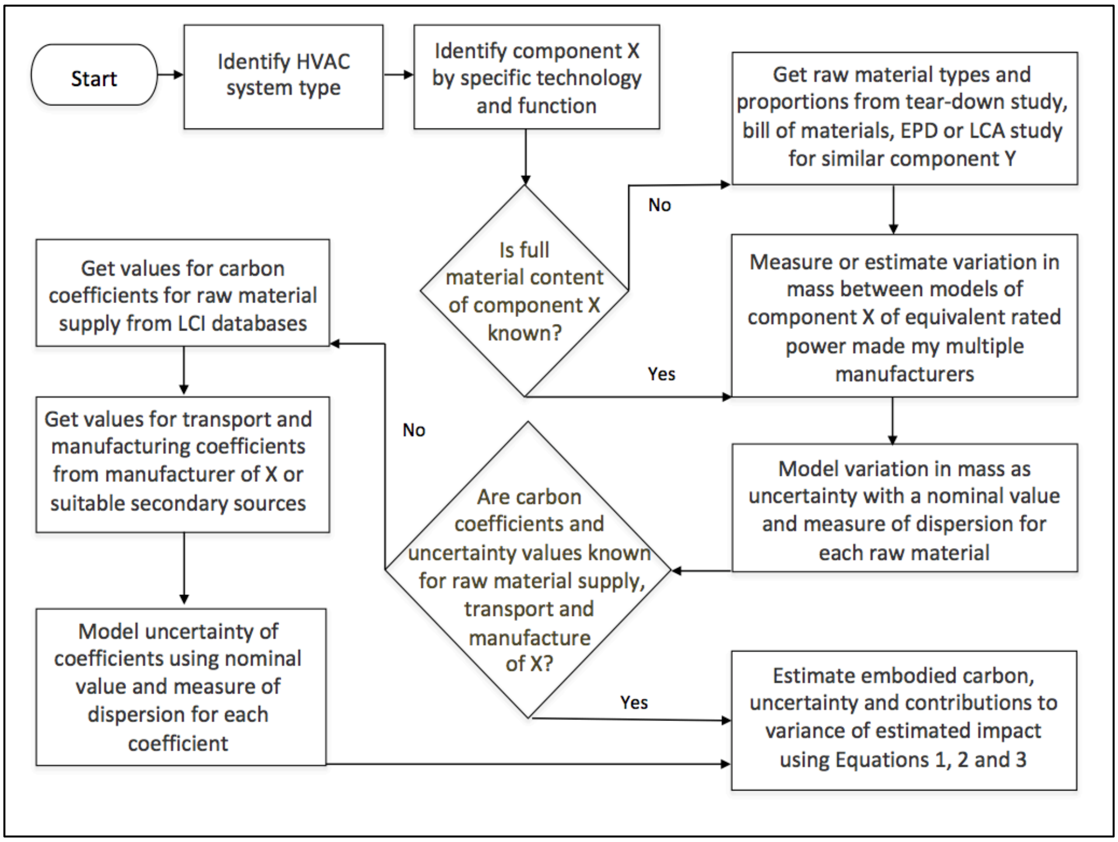

Figure 5-20: Decision-making flowchart for EC estimation method

5.6 Chapter summary

A series of case studies has been used to demonstrate a method to estimate the nominal value and uncertainty range of product stage embodied carbon (EC) for composite HVAC components, based on default input values for raw material masses and EC coefficients, both of which were subject to uncertainty. Results obtained using first order analytical uncertainty propagation (AUP) do not differ significantly from those derived using Monte Carlo simulation (MCS) with 10,000 simulation runs, whilst at the same time being arguably more efficient computationally. The method is shown in principle to be able to support comparisons of embodied as well as operational impacts of equivalent HVAC components as well as comparisons between embodied impacts of HVAC systems at building level. A sensitivity analysis of the findings shows that the use of alternative life cycle inventory databases has a significant effect on estimated mean embodied carbon values but does not affect the ability of the method to make meaningful distinctions between the impacts of alternative HVAC systems.

What are the limitations of the proposed method? A more detailed discussion of the limitations and how their effects were mitigated is presented later in chapter 9, although these can be summarised for now as follows:

- Practical challenges experienced around data collection meant that a wider range of generic composite components and types of HVAC systems could not be investigated in depth. Additional studies of composite components other than fan coil units would have supported retesting of the finding from section 5.4.1 that embodied carbon relative to mass falls as the size and power rating of the component increases.
- The scope of the LCA methodology used was mainly limited to the product stage of building services systems considered. Recurring and end of life embodied impacts were not considered while operational carbon emissions were considered within the study of fan coil units but not included in the uncertainty analysis.
- The first-order method of uncertainty propagation could have been extended to the second order of the Taylor series ((Mekid and Vaja, 2008, Pfingsten et al, 2017) to better represent non-linear errors.

The dependency of the estimation method on life cycle inventory data that may be incomplete is also addressed by the schematic in Figure 5.20 and the general process model described later in chapter 8 and illustrated in Figure 8.2.

6 Decision-making in HVAC systems design

6.1 Introduction

This chapter addresses the third research objective, which is to investigate decision-making about the design of HVAC systems for office buildings using the results of a qualitative study of mechanical building services engineers in the UK. The study links with and supports the embodied carbon estimation method in two ways. Firstly, it draws on the experience of practitioners to clarify the definition and boundaries of HVAC systems used to build the LCA model and secondly it clarifies the practical context in which design decisions that might be supported by a tool to estimate embodied impacts are made. This context includes the decision-making process and the user requirements for the tool, important elements in helping to align the specification for the tool to the type of decision and decision maker likely to be found in a practical HVAC design environment. The examination of the decision-making process uses a theoretical framework that tests the classical economic assumption of rational behaviour that underpins the LCA model. This is because alternative explanations of decision making that are based on Simon's theory of bounded rationality (1981), which are also tested, offer more depth of insight into the complexity of decision making in building design teams, where the preconditions for rational choice cannot always be assumed to exist. Such an assumption has been identified previously as a flaw in the LCA model (Bras-Klapwijk, 1998), therefore the work in this chapter represents a way to make an LCA-based embodied carbon estimation method more theoretically robust as well as being better suited to use by practitioners in building design. Overall, the chapter's outcomes are (a) clarification of the definition and boundaries of HVAC systems; (b) clarification of user requirements for the HVAC selection tool; and (c) a coherent theoretical understanding of decision making informed by practitioner experience.

A description of the study methodology is provided, which builds on the general outline provided in chapter 3 and focuses on the methods used for data collection and analysis. The results are then discussed in relation to the background context and the processes involved in making design decisions about HVAC systems and components. Responses from the interviewees to questions on the classification and definition of HVAC systems are compared with equivalent information from research literature, to help identify the most typical HVAC systems used in offices and the definition and boundaries of these systems. This helps clarify the system boundary of the LCA model used for embodied carbon estimation in chapter 5. Issues discussed around decision making include the actors involved, the timing, the design priorities, the mechanism used to select options and the opportunities for intervention to reduce environmental impacts including embodied carbon. The theories of rational choice and bounded rationality are then considered as possible frameworks to explain the way that decisions are made about HVAC design. This is achieved by analysing the findings via themes associated with areas of decision-making theory that help explain behaviours adopted by participants. Conclusions are drawn and implications outlined for the application of a decision support tool that identifies embodied carbon impacts of alternative HVAC options, after which limitations of the analysis of decision-making are outlined.

6.2 Methodology

6.2.1 Overview

This chapter is linked to the industry survey in chapter 4 by a sequential explanatory mixed methods research design, in that the qualitative study holds the potential to provide greater depth of understanding on topics identified in the survey. The survey suggests that influence of multiple stakeholders, multiple priorities, and the timing of key decisions all – to a greater or lesser extent – have an impact upon the decisions made to choose options for HVAC systems and components that are specified in a building design. This chapter uses a mainly qualitative social scientific approach (the semi-structured interview) to explore that complexity, as well as providing clarification on two topics that inform other research objectives. The definitions and boundaries of HVAC systems and the user requirements for an embodied carbon selection tool for HVAC systems are also key elements for this part of the research study. The approach to theory development used in this chapter is deductive in that it tests existing theories of rational choice and bounded rationality against empirical evidence.

6.2.2 Sampling strategy

A broad target group was identified of mechanical building services engineers who held the lead responsibilities for design decisions on HVAC systems within building design teams and had experience of working on office projects. To access this target group, invitations were extended to two sub-groups. The first were respondents from the online industry survey discussed in chapter 4, of whom 27 had indicated their willingness to be interviewed to discuss important topics in more depth. Of these, 19 were employed by the project sponsor (AECOM), a multi-disciplinary global consultancy working in the built environment, and 8 worked for other organisations. The second group was composed entirely of at least 100 mechanical services designers known to be employed by AECOM across the UK who had not previously been contacted. As only 3 of the first sub-group worked designing mechanical services and were still available for interview, recruitment of the second sub-group was boosted via regional Continuing Professional Development (CPD) seminars within the project sponsor organisation, to disseminate earlier research findings on resource efficiency and building services. Topics covered by the interviews were excluded from the CPD sessions to avoid bias from any observer-caused effect. This led to the recruitment of 16 more participants, making a total of 19. The interviews took place between October 2016 and January 2017, lasted for 45-60 minutes each and were all audio-recorded and transcribed for analysis (see below)..

6.2.3 Interview structure

The topic guide for the qualitative interviews, a copy of which is provided in Appendix 5 consisted of six complementary sections. A section on possible classification and definitions of air-conditioning systems was followed by two sections on design decision-making, the first considering choice of system and the second on the sizing, layout and specification of components within a system that had been chosen. The last two sections dealt respectively with reducing embodied carbon and possible user requirements for an embodied carbon estimation tool for HVAC systems. The sequence of topics was designed to elicit the participants' own understanding of the design decision-making process and reasons why particular options were chosen. Subsequent questions considered how these decisions might affect embodied carbon and whether embodied carbon might be considered explicitly during the decision-making process.

6.2.4 Data analysis

The interview transcripts were coded and analysed thematically, employing an approach based on a modified list of the techniques set out by Ryan and Bernard (2003). Coding of transcripts was implemented using dedicated macros written in VBA (Visual Basic for Applications) to identify terms by frequency of use in Microsoft Word. The identification and analysis of themes was implemented using the following steps:

- Stage 1 - Selected observational techniques: Reading and re-reading the text, identifying repetition, local terms and meanings, similarities and differences and theory related material likely to support the testing of two alternative theories of choice, rational choice and bounded rationality. Rational choice, as described in section 2.7, requires the assumptions of completeness and transitivity of alternatives, maximisation of utility and independence of irrelevant alternatives (Coleman and Fararo, 1992), definitions of which were provided in section 2.7. By contrast, bounded rationality is based on heuristics and relies on simplified rules for searching for options, stopping the search and making the decision (Simon, 1981, Gigerenzer, 2002). A critical distinction is that rational choice relies on optimisation based on complete knowledge of all available options and their performance against criteria, while bounded rationality relies on satisficing, using cues to guide choice based on incomplete knowledge of options and criteria. As explained in section 2.7, rational choice is used because it can represent a kind of default assumption underlying reference literature on decision support for engineers. The choice of bounded rationality as an alternative explanation for decision-making enables both theories to be compared within a positivist framework (Stingl and Geraldi, 2017) in keeping with the overall theoretical approach of this study.

- Stage 2 - Processing: Development of themes using an *a priori* approach, by drawing on question categories and themes previously discussed in the industry survey and research literature. The themes considered include barriers and drivers associated with reducing carbon emissions and aspects of decision-making theory associated with bounded rationality such as bias, heuristics and framing that help explain behaviours of participants.
- Stage 3 - Analysis of the two areas of theory in the light of the experiences of interview participants as seen through the themes identified.

6.3 Characteristics of the sample

All of the 19 participants interviewed were mechanical building services engineers employed by the project sponsor, based at offices in London, St Albans, Bristol and Cardiff. The median and the mean number of years worked in the construction industry were both equal to 18. For many, this included experience in other UK construction firms, so the employment history of participants was not limited to the sponsor company. While participants had worked on many types of buildings, their combined experience covered at least 100 projects on office buildings in the UK and elsewhere, in which they had held the lead responsibility for the design of mechanical services including HVAC systems.

6.4 Main findings

6.4.1 Definitions of HVAC systems and most common examples cited

Interview participants were initially asked to identify the five most common types of air-conditioning system being designed for medium to large UK office buildings. These were defined as office buildings with over 1000 m^2 in floor space, designed currently or within the last ten years. The interviewees were invited to comment in response to a diagram based on a building services reference guide (Oughton and Wilson, 2016). The diagram, which is reproduced in Figure 6.1, firstly describes air-conditioning systems, which also belong to the broader category, HVAC systems, as they must by definition also provide cooling and ventilation and, if operating in the UK climate, heating. The diagram does not show the primary heating or cooling sources, such as boilers or chillers, required by centralised and partially centralised systems, because each type of primary system can be compatible with many of the secondary systems shown on the diagram. However, the diagram does show alternative options of mechanical, natural and mixed mode ventilation, as these also impact on the final HVAC configuration, even though these options do not all deliver full air-conditioning. Interview participants were also encouraged to indicate where the categories or relationships in the diagram should be amended, if applicable, to reflect their understanding of how systems should be classified.

The question had two principal aims. The first was to validate or challenge the results of desk research used to identify 'typical' generic HVAC systems suitable for use as case studies in chapter 5. The second aim was to verify whether practitioners agreed with the hypothesis that generic, alternative types of HVAC systems existed with distinctly different types of technology, as opposed to HVAC systems being infinitely variable and impossible to classify by type. This is relevant because the existence of identifiable types of HVAC system means in principle that raw material and other inputs may be sufficiently different between systems - and sufficiently similar within each type of system - to enable estimation of embodied carbon impacts by system type.

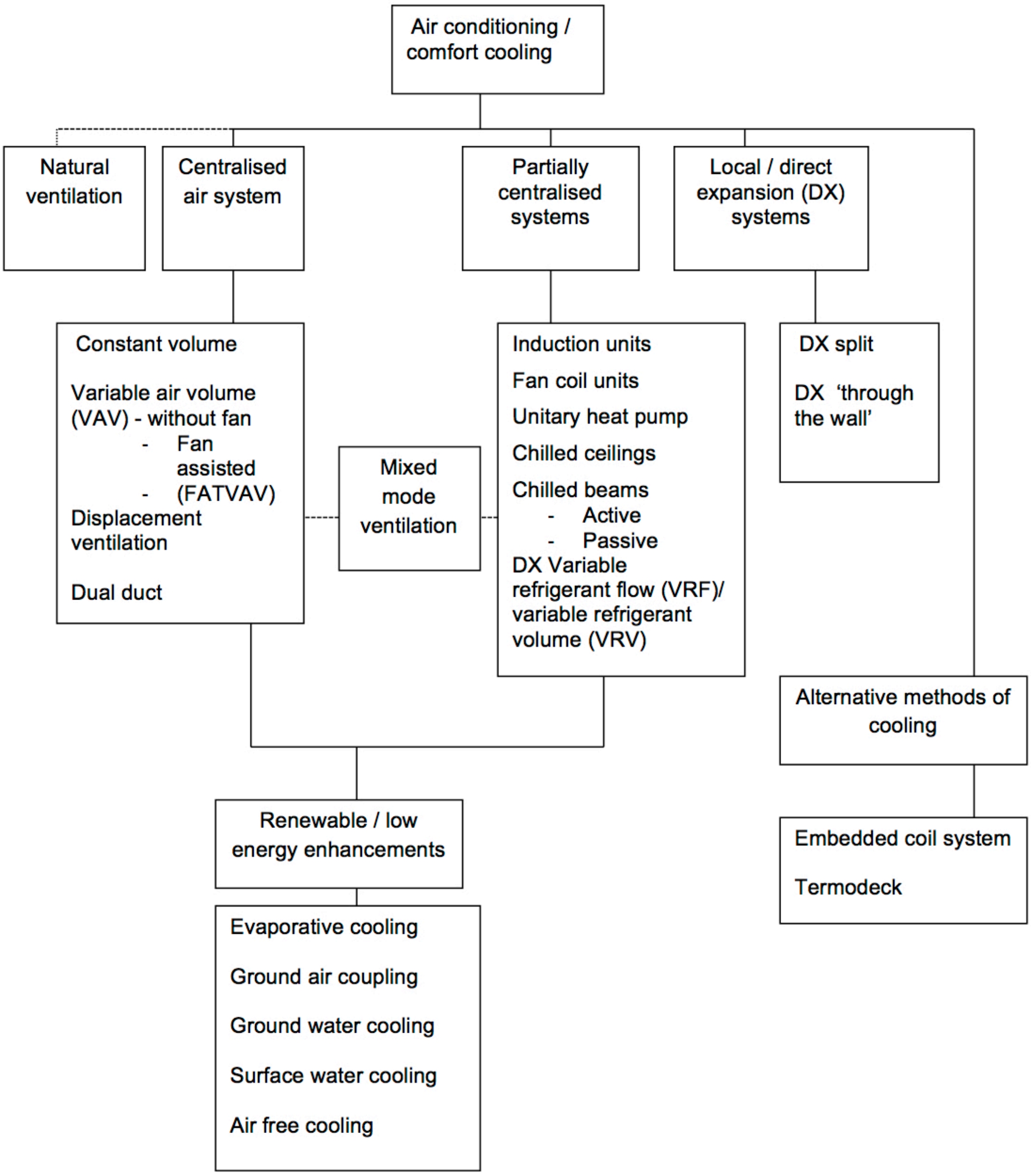

Figure 6-1: Generic types of air-conditioning system, based on Oughton and Wilson (2016, p.506)

Interview participants generally were of the opinion that HVAC systems fall into identifiable types although there are differences on how systems should be classified and on whether projects to design particular systems were common within current workloads. Direct quotations from three of the interviews that illustrate this point include the following:

'Some of these things like VAV you could argue could fall under partially centralised depending on what type of VAV'. (Participant A, 27 years in industry).

'You might have a fan coil unit system with a constant volume, or you might have a fan coil system with a variable volume'. (Participant B, 14 years in industry).

'I think a fan coil unit would generally be centralised'. (Participant C, 20 years in industry.

The results on the five most typical system options in the experience of interview participants, shown in Figure 6.2, are broadly in line with findings from a BRE survey (Abela et al, 2016), shown in Table 6.1 in which the three most common types of air-conditioning system in UK office buildings as single or multi-split systems including VRV, followed by fan coil unit and VAV systems.

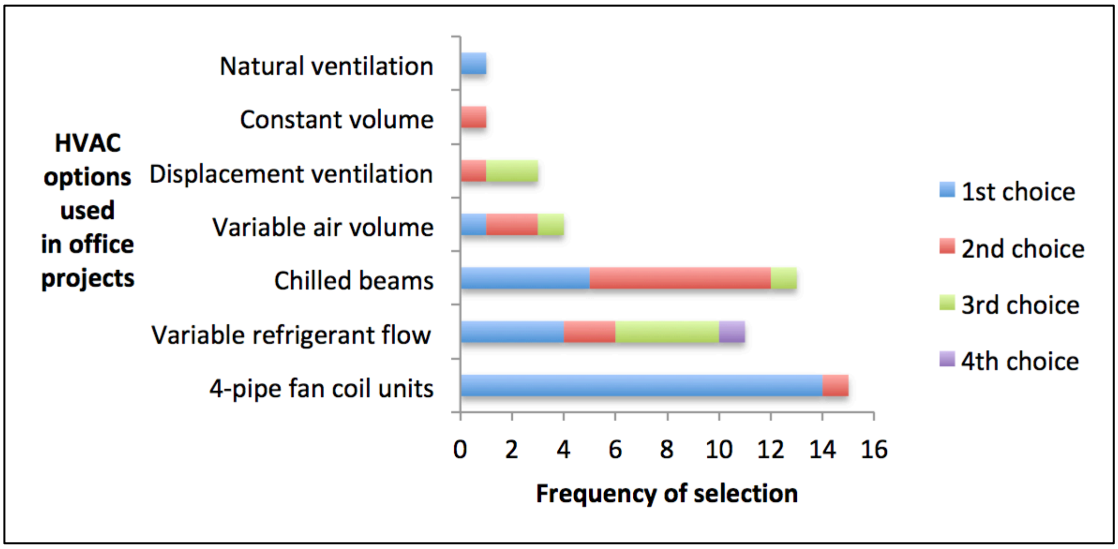

Figure 6-2: Most common HVAC systems as ranked by interview participants

The BRE categories are not precisely equivalent to those in Figure 6.1, as the BRE sample includes offices with less than 1000 m^2 in cooled floor space, while the categories in Figure 6.1 include natural ventilation, which falls outside the definition of an air-conditioning system. However, if the 'single room cooling systems' used in small offices are excluded as a category and the single split systems also used in small offices are excluded from the split/multi-split category, the six most common air-conditioning systems found in the BRE survey match five of the six most common HVAC systems identified by interview participants. This comparison is more appropriate because the interviewees were asked to describe systems for office buildings with over 1000 m^2 of floor space and this category resembles the sample of office buildings covered by the

BRE survey once the single split systems are excluded.

Table 6-1: Findings of BRE survey on air-conditioning systems used in UK office buildings (Abela et al, 2016)

Type of air-conditioning system	Number of buildings in sample	Total cooled floor area (m^2)	Average cooled area per building
Split or multi-split system (multi-split includes VRF/VRV systems)	127	86,923	684
Fan coil systems	37	98,343	2,658
Single-duct VAV	16	51,639	3,227
Single room cooling systems	5	413	83
Chilled ceilings or passive chilled beams and displacement ventilation	4	44,368	11,092
Constant volume (fixed fresh air rate)	4	14,603	3,651
Indoor package cabinet (VAV)	2	2,206	1,103
Induction system	2	7,936	3,968
Dual duct VAV	1	10,628	10,628
Terminal reheat (constant volume)	1	69	69
Active chilled beams	-	-	-
Constant volume (variable fresh air rate)	-	-	-
Dual duct (constant volume)	-	-	-
Water loop heat pump	-	-	-
Total	199	317,128	

A key aspect of responses on the definition of HVAC systems is the relationship between physical features of the building and choices of HVAC systems. Most participants took the view that '…building constraints are likely to decide the choice of primary systems', (Participant F, 32 years in industry), while one also commented on the implications of spatial constraints for secondary systems:

> *'If it's a new build, it's a shell and core, the shell and core would be designed to accommodate plant [for primary systems]… so if we were not designing the shell and core, we should know what our options are [for secondary systems]… The options… have different impacts… especially when you are looking at centralised air systems vs. partially centralised, because they have a fundamental difference in plant space, riser space, those two options'. (Participant B, 14 years in industry).*

These views suggest that the options possible for the overall HVAC system will be influenced firstly by spatial constraints and secondly, for systems that are wholly or partly centralised, by the effect of particular choices of primary systems on the options available for secondary systems. This has implications for embodied carbon estimation and for the understanding of decision-making in HVAC systems design. The interdependency of primary and secondary systems means that embodied carbon impacts should be estimated for both parts, whilst the decision-making process may involve key decisions on HVAC system configuration happening at different times during the timeline of building design. The next section therefore focuses on perceptions about the way that decisions are made on HVAC system design.

6.4.2 Decision-making

Interview participants were asked to explain how and when decisions were made to choose HVAC options for an office building, who was involved, what the decisions were based on and what kind of information was available to support the decisions. The aim of the question was to test whether the preconditions for rational choice or some form of bounded rationality could be identified in the environment in which practitioners were working. Such an understanding of how decisions were made could in turn inform the design of a decision support tool intended to help practitioners make decisions associated with reducing embodied carbon. The interviewees were also encouraged to elaborate on how their answer might vary for new build, refurbishment or fit-out projects.

6.4.2.1 Stakeholders and timing

As mechanical building services designers, the interview participants explained that their role entailed taking the lead in advising the building design team on HVAC system design. Several interviewees referred to their role in decision-making around the HVAC system type, which potentially began at a very early stage; for example: "…*we as building services engineers are involved in the earliest stages, the feasibility stage of a project"* (Participant G, 26 years in industry); and *"…it's stage one or stage two decision depending on how mobilised people are, because it sets out how ceiling heights and massing and everything else comes out of the back end of the system selection"* (Participant E, 18 years in industry). The balance of influence to shape these decisions between the interview participants and other team members would in turn depend on the circumstances of the project. A critical part of these circumstances was timing and the specificity of the client's design brief. The results of the online survey outlined in chapter 4 showed that ‘early design decisions on the building form and level of servicing’ were seen as more important by the majority of survey participants than the choice of the type of building services systems or products for the purposes of environmental resource efficiency. This was reinforced by perceptions of participants in the qualitative study. For instance, some emphasised that the extent of their own level of influence on decisions about HVAC system type would depend largely on whether or not they were involved in the early discussions about building form and structure, as such discussions would narrow down the range of HVAC options. One interviewee referred to the lack of flexibility around decision choices that can occur in circumstances that involve ‘informed’ clients: “*If you’ve got informed clients…they have their standard engineering brief and that would describe what they want within their office, which makes life in theory a lot easier but then doesn’t give you the flexibility to look at other options* (Participant H, 28 years in industry).

Overall, the responses around levels of influence gathered in the interviews help to give greater clarity on another aspect of the survey findings outlined in chapter 4. It was noted there that in the survey, building services designers and construction clients were identified as the two groups of stakeholders with most influence on whether building services were efficient in their use of natural resources. The interview responses suggest that where an informed client has a specific project brief or does not consult mechanical services designers until after RIBA stage 2, by which time the concept design has been agreed, the client will tend to be more influential than the designer in choosing the type of HVAC system. This interviewee highlighted how influence can vary substantially from one project to the next:

> *‘Who’s got the most influence- it depends on the project really. If it’s a shell and core office… then when you turn in the services strategy for the offices in the building, potentially the developer has the most influence because he’s the one paying the bills and he’s going to have an opinion on that. It can be the architect because they want to see how the fit-out’s going to be. But then again if it’s going to be a very low energy building then we might have the most influence, because*

you know you want a low energy, we've got to tell you how it's going to be'. Participant I, 16 years in industry.

In terms of choice theory, the presence of constraints on the scope of available options, such as limitations associated with the building form and available spaces for services to be installed does not prevent rational choices being made after the designer is involved (Gachter, 2013). However the need to make a quick decision on the type and location of primary HVAC systems may necessitate satisficing, which can indicate bounded rationality. Without taking a view on whether rational choice or bounded rationality enables the most appropriate design decisions to be made on a project, identifying the theory best able to describe decision-making practice has value in shaping a decision support tool. For more theoretical insight it is therefore necessary to tease out the processes used to arrive at decisions on HVAC system design.

6.4.2.2 Process used to make decisions

For decisions on HVAC system design in which the interview participants had some involvement, a common response was that where the client brief was not limited to a single prescriptive design option, an appraisal of several options could be prepared in which each option could be compared against a set of criteria and either given a score or presented for discussion. However, participants differed on the exact approach taken. There was firstly variation in the preconditions needed to prompt the use of an option appraisal, with one participant indicating that it would be used on *'…99 out of 100 jobs'* (Participant E, 18 years in industry) and others suggesting that it would only be needed on *'bigger projects'* (Participant C, 20 years in industry) or if a client had requested *'…a full blown analysis'* (Participant N, 28 years in industry). Variation was also seen in whether participants as mechanical services designers would share the full appraisal with the client or conduct it internally and whether, if the appraisal was shared, they would recommend an option. In the absence of a formal option appraisal, participants also indicated that HVAC designs could instead evolve iteratively through discussions with clients, especially if the client was technically knowledgeable but had not initially provided a prescriptive project brief. The three main variations of the process used to select an HVAC system were therefore defined as (a) exploring a single option provided by a prescriptive brief from the client; (b) comparing multiple options via a formal appraisal against design criteria; and (c) developing an option iteratively via discussion with a technically knowledgeable client.

Overall, participants' views varied between those who saw option appraisals as an objective way to make comparisons and those who took the view that they were necessarily subjective, either because the designer might*'...weight it [the report] to suit whatever you want to do'* (Participant B, 14 years in industry), or because it was *'...very easy to end up comparing the best of something with the worst of something'* because of a variable quality of information about the performance of different equipment (Participant I, 16 years in industry). Some participants based outside London also indicated that their explicit preferences and/or recommendations when comparing HVAC options in discussions with clients would begin with natural ventilation, followed by mixed-mode and lastly full mechanical ventilation.

The responses indicate that building services designers may have explicit or implicit preferences for particular HVAC options on a project. An explicit preference for natural ventilation might entail a reduction of embodied as well as operational carbon, although this option is not seen as commercially viable for projects in central London due to adverse environmental conditions. The designer's preferences may or may not influence the way in which options are weighted explicitly in an appraisal or favoured in discussion with a client, but in either case, such preferences can be consistent with the assumption of rational choice. This is because a preference for particular options might be a way to maximise utility, thus if passive design measures are perceived to have intrinsic utility, natural ventilation would represent a rational choice. However, as rational choice as formally defined also requires complete knowledge of available options (Coleman and Fararo, 1992), a follow up question sought to investigate the nature of information available to participants about alternative HVAC systems.

6.4.2.3 Information available on HVAC systems

Participants were asked to describe the information typically available to mechanical building services designers about the suitability of various HVAC systems, in order to test whether the assumption of complete knowledge of alternatives required by the theory of rational choice could be supported (Coleman and Fararo, 1992). The replies divided evenly between those who considered information equally good about all options and those who did not. Those in the former category cited reasons such as levels of in-house experience and the ease of access to technical information on the internet, while those in the latter category gave specific examples of HVAC options for which less information was in their view available. This included the view that there was '*…less historical data around natural ventilation systems and how they perform than there is about air-conditioning systems*' (Participant F, 32 years in industry). Another example was the view that systems currently prominent in the market such as chilled beams, fan coil units and VRF were better served by manufacturers' information than a system like displacement ventilation, that '*…relies on us a lot more to develop that design'* and was consequently '…*a bit more risky for us as a company where they're relying on the engineering skills to demonstrate that that system will work'.* (Participant M, 12 years in industry).

These clear differences in perceptions on completeness of information could either indicate that participants differ in their individual levels of knowledge of available options, or that regardless of individual knowledge, perceptions differ on whether access to sufficiently complete knowledge of all options is possible. Either case would mean that the assumption of complete knowledge required by rational choice fails and that bounded rationality might better describe the conditions under which choices are made. Moreover, as indicated by the literature review in chapter 2, the scarcity of information on embodied carbon of any given design of building services would also hinder a rational choice of HVAC options if embodied carbon values were needed as a decision criterion.

6.4.2.4 Decision criteria

Whilst variations were described in stakeholder influence, timing, mechanisms and supporting information involved in decisions about HVAC design, participants generally took the view that the decisions were based on some kind of criteria, rational or otherwise, however many options were considered. In a formal option appraisal, the criteria might be represented by a list of parameters of each option that could be given a score by the designers. This is exemplified by the template in Table 6.2, which summarises the format used on an appraisal conducted by the project sponsor in 2017. The table combines parameters such as operational energy impacts for which a score can be based on quantitative estimation using an energy model and parameters such as aesthetics requiring a score based on a value judgement. Unusually, the table also includes embodied carbon as a parameter, as the client in this case had a particular interest in whole-life environmental impacts and the research conducted for the present study was available as a data source.

Table 6-2: Example of scoring template for HVAC option appraisal (AECOM, 2017)

Parameters	Scores for HVAC system options (summarising rankings by the design team on a scale from 0 to 2, with the highest score representing the most beneficial)		
	Option A	**Option B**	**Option C**
Costs:			
• Capital costs	0	1	2
• Operational costs	2	1	0
• Plant-space requirements	1	1	1
• Construction programme costs	1	2	2
Sub-total	**4**	**5**	**5**
Aesthetics	1	2	1
Health, wellbeing, thermal comfort:			
• Indoor air quality	1	2	1
• Acoustics	1	1	0
• Audible privacy	1	1	1
• Draughts	1	1	0
• Thermal comfort	2	1	1
Sub-total	**6**	**6**	**3**
Energy, sustainability			
• Energy in use	1	1	1
• Embodied carbon	1	2	1
• Pollution	2	1	1
Sub-total	**4**	**4**	**3**
Technical performance, flexibility			
• Capacity	1	2	1
• Controllability/adjustability	1	2	1
• Temperature control-band	1	2	2
• Tenant fit-out flexibility	2	1	1
• Maintenance	2	1	1
Sub-total	**7**	**8**	**6**
Overall total	**22**	**25**	**18**

By contrast, several participants pointed out that for some projects where a prescriptive client brief decided the choice of HVAC system, the client's preference would be based on a single criterion, which might not the 'right' choice for the building from their perspective as designers, because it was decided without considering parameters against which other systems may have scored better.

> '*... If it's a developer that's developing for spec [i.e. a speculative development] a letting agent would say 'Well if you want to let this building, or this office floor, the current trend is fan coil units. That's what my clients would use'. It's not always the right way because sometimes they are a bit behind. They know the tried and tested but sometimes not the new approach'.* Participant B, 14 years in industry.

These two contrasting examples - system selection using either an option appraisal or on the basis of a single, dominant criterion - at first appear to illustrate rational choice and bounded rationality. The option appraisal seems to enable a clear ranking of all three options based on a measurable total score, which would make the options transitive, the scoring could be said to measure utility against each parameter and the scoring of all parameters for each HVAC system could represent complete knowledge within the constraints of those three options. Similarly, the developer's preference for fan coil units could be seen as boundedly rational because a rule of thumb, or heuristic - to choose the option that they thought most marketable - was used to eliminate all other options from consideration. In so doing, the developer may be satisficing, making a choice based on incomplete information, as the preconditions for rational choice would require that other options were considered, just in case they were more marketable and would therefore have a greater utility value.

Out of these two interpretations, the rational choice interpretation offers a less effective explanation of the scenario described as it relies on the assumption of complete knowledge of alternative options. Even if relatively complete knowledge is available to designers about each option that is being compared, the metrics used to compare performance of HVAC systems may not fully and objectively draw on this knowledge, which for one participant could mean that gains in resource efficiency are undervalued.

> '*The building regulations assume that all supply air is brought at an external temperature. But in reality if you do a fan coil unit system that's not true. You will always warm the air up to just below room temperature. So building regulations assumes you've got a huge amount of free cooling of the fresh air you put into a building. If you've put a fan coil unit system in reality you don't. So it'll make a fan coil unit system look more efficient than it actually is. Whereas a VAV system, you will get an advantage from free cooling, because you can bring in air… directly and not have to do any active cooling… but you don't see that benefit in the building regulations calculation'.* (Participant I, 16 years in industry).

6.4.2.5 HVAC sizing, layout and raw materials

Interview participants were asked what factors influenced (a) decisions on the sizing and spatial layout of an HVAC system and (b) the raw material composition of individual components that were specified, once the choice of HVAC system had been made. The aim here was to explore whether any variation existed in the quantity and type of raw materials used in the design of a given system for a given building. The rationale for the question, as outlined in chapter 2, is that embodied carbon can be reduced either by using less of an existing raw material or replacing raw materials with alternatives that are lower in embodied carbon. As the case studies of HVAC systems in chapter 5 indicate that distribution components such as pipework and ductwork might make up more than half of the embodied carbon of the system, the question on spatial layout mainly applied to these components, while sizing might apply to all types of components - central plant, distribution and/or terminal units.

The predominant view among interview participants was that the sizing and layout of HVAC systems were influenced by three main factors - spatial building constraints, thermal loads and relevant standards. The standards most cited in interviews were the British Council for Offices (BCO) standards on system layout (BCO, 2014). The drivers for designing a layout of pipework or ductwork that was economical in its use of raw materials were seen as the relative simplicity of producing a more 'elegant' design and the cost savings rather than the amount of raw materials saved. Most interview participants considered that in responding to spatial and other constraints it was unlikely that there would be variations of more than 10-20% in material use between HVAC distribution layouts designed for the same project by any two designers. A contrasting view was expressed by one participant who felt that there was *'…a huge amount of room'* for variations in material use between designers, using an example of many types and sizes of metal or plastic air diffusers being compatible with the same type of air-conditioning system*.* (Participant I, 16 years in industry). In terms of choice theory, both perspectives could be consistent with rational choice but differentiated by the extent of the constraints perceived to limit the design options.

Regarding the sizing of central plant such as boilers and chillers, most interview participants agreed that general industry practice was *'…traditionally oversized'* (Participant D, over 20 years in industry), both in the plant selection criteria recommended in relation to particular thermal loads and in the additional design margins added during the project design process. This was attributed, for instance, to the fact that *'…everyone builds a safety factor into their design - if in doubt, go to the next size up'* (Participant J, 15 years in industry). Examples were offered of what were seen as valid reasons for oversizing, to accommodate uncertainty about thermal loads and ensure future flexibility of speculative office space, but the point was also made that with the modern capabilities of thermal modelling, excess oversizing should not be happening. These responses suggest broadly that there is some scope for variation in both layout and sizing of HVAC systems to meet a given set of criteria in a given building but that material resource efficiency is not normally a factor driving HVAC design, except indirectly where reduced distribution runs or plant sizes are also associated with savings in operational energy or capital cost.

This impression was reinforced by responses to a question on what might inform the choice of raw materials in a specification for HVAC components, which were typified by the statement that '…*standard practice by far and away dictates the materials that are used in services*' (Participant J, 15 years in industry). It was explained by most interview participants that standard practice entailed not considering raw material content unless it affected operational performance or cost. Examples were provided in relation to components used in HVAC distribution that tend to be made of a single raw material. Ductwork was usually specified to be made of galvanised steel as fabric ductwork was considered *'…a bit untried and tested'* (Participant D, over 20 years in industry) and plastic ductwork was specified only when there was a need to reduce weight, to fit into tighter voids and spaces or for applications like fume cupboards in which steel ductwork was not appropriate. Pipework tended to be specified as steel or copper as designers were said to lack confidence in plastic pipework, although the ultimate choice of material procured was *'…driven by contractor preference in* *terms of financial cost and ease, speed of installation'* (Participant P, 5 years in industry). Regarding composite components, the raw materials used in terminal units and central plant were also said to be not considered by the services designer responsible for the specification, except when there was a particular implication for weight, cost or performance of the component. The relevance of weight as a selection criterion for composite components echoed a view expressed about ductwork that '*…the choice has never been about materials. It's been driven by weight... and also space'* (Participant E, 18 years in industry).

The responses suggest that decisions on sizing, layout and raw material choice by HVAC designers are not normally driven by material resource efficiency, although some decisions made for other reasons can have outcomes that either use fewer raw materials or materials that have less embodied carbon than would be the case with a conventional alternative. There are secondary challenges on raw materials and layout, in that that building services contractors have some flexibility in procuring products to meet a design specification and in altering the spatial layout of services as drawn or modelled by the designer. However, the focus of the current study is on the role of the designer, whose influence remains significant as the person or team producing the mechanical services specification and layout within the building design.

6.4.3 Reducing embodied carbon

Interview participants were then asked whether they considered it possible for designers to reduce material use or embodied carbon in HVAC systems, using the information available on a typical office project, and if so, how? The aims of the question were to explore the scope for increasing resource efficiency of building services without additional decision support and to test awareness or understanding of good practice as outlined in the CIBSE publication that led to this study (CIBSE, 2014a). The responses were varied. A widely expressed view was that reduction of material use or embodied carbon was not currently seen by building services designers as a priority, except where it was specifically required by the client in the project brief. However, there was also support for the view that more could be done, both by increased recognition of existing design activities that indirectly increased resource efficiency and by deliberate changes to amounts or types of services equipment in a building. For instance, one participant stated that '*a lot of the time we're working for a contractor, so we're very much driven by making the design as low capital as possible so as part of that we probably do look at how to lay out the systems efficiently'.* In such a case, to highlight the idea that the design was also reducing embodied carbon could offer '…*a far more positive spin on something that a client would actually pick up on'* (Participant M, 12 years in industry). Another approach involved rethinking the system design:

> '*…In terms of reducing the amount of material in a building … you need to take a step back and think why are we putting active systems. Ventilation you can use, instead of doing supply and extract you could have a plenum ceiling. You've got rid of up to 50% of your ductwork by having common extract… sizing of radiators, you can make radiators smaller if they're hotter… so if you raise your system temperatures then you have less, smaller terminal units'* (Participant P, 5 years in industry).

It is significant that proposals to decrease material use by optimising the spatial layout of HVAC systems or by replacing extract ductwork by using a ceiling void as a plenum are also specific recommendations made by CIBSE to increase the resource efficiency of building services (CIBSE, 2014a). This confirms that although embodied carbon reduction may not be a priority within industry standard practice, some participants are aware of methods to achieve it and believe that it is achievable.

What are the implications of current practice on reducing embodied carbon in HVAC systems for rational choice theory? As embodied carbon reduction is not widely seen as a priority, although it may happen as a side effect of design choices made for other reasons, designers may not always ensure that they have access to information on embodied carbon impacts when making decisions, even if that information is readily available, which it may not be, as discussed in chapter 2. Although this would not impede a broad strategy to use fewer raw materials overall, a lack of quantitative data on embodied carbon would hinder the theoretical completeness of information needed to make a rational choice between two or more alternative designs for any one HVAC system. There are therefore at least three reasons why bounded rationality may apply to decisions on HVAC systems and components if embodied carbon is a criterion of choice, one of which is contextual and the other two cognitive. The first is the lack of embodied carbon data, which makes the decision-making context lack complete information on design options. The second is the perceived lack of importance of embodied carbon as a construction industry priority. The third is the effect of 'standard practice' on oversizing of central plant and limiting the range of raw materials specified for HVAC distribution components.

6.4.4 Re-using existing HVAC components

Interview participants were also asked what might be the drivers for reuse of existing components on refurbishment and fit-out projects that respectively involved major or minor changes to existing buildings with existing HVAC systems, and how reuse of components might be increased. The aim here was to assess the scope for embodied carbon reduction via reuse. The general response was that drivers for product reuse were the decision to undertake a survey of the condition of existing components, the suitability of the component against the requirements of the new project design and the component's condition, which would include its age against industry benchmarks for economic life and its serviceability. It was also noted by some that distribution components such as pipework and ductwork were less likely to be reused than items such as chillers, boilers, pumps, air handling units and terminal units, either because it might only be seen as cost-effective to reuse higher value items or because certain items such as pipework were expected to degrade quickly.

The view that a condition survey of equipment would drive its reuse did not fully explain whether the initiative to implement the survey was coming from the designer or the client. Examples were given of both types in which the survey had been proposed, either by the designer or the client, because of the potential savings in capital costs, indicating that at least sometimes it is within the discretion of the designer to recommend reuse. Participants also described a converse scenario in which HVAC equipment that in their view should have been reused, was discarded prematurely.

'…There have been situations where… systems aren't that old and they've just been ripped out and replaced. It does happen especially when... you've fitted a building out to a Category A[1]*. I've seen it so many times where it's been fitted out and… the tenant may only have come on board during the construction process and has been unable to influence their requirements for the space, or because of contractual difficulties. So they've gone in and fitted out to Category A space and then the tenant takes it and rips it out'* (Participant A, 27 years in industry).

Interview participants offered a range of views on how reuse of HVAC components might be encouraged, including policy and market incentives and greater collaboration.

'…If there was a benefit that sat in Part L or in GLA (Greater London Authority), something that made an incentive for reuse, it would target people to work harder (Participant E, 18 years in industry).

However, there was also a general view that the main driver would be greater buy-in from construction clients, as clients were responsible either for deciding to incur costs by replacing existing installations or choosing to make the savings and manage any risks associated with equipment that was reused. It was also suggested that cost savings were likely to be a more effective incentive than circular economy benefits in persuading clients to reuse HVAC equipment. Given the importance of cost incentives to clients, rational choice theory may not fully explain why cost savings via equipment reuse are not often explored as an option, therefore a cognitive factor of unfavorable industry perceptions towards reuse may be present, in which case bounded rationality would also apply to decisions on whether to reuse equipment.

6.4.5 Proposed HVAC selection tool

The final section of the interview sought feedback on potential user requirements for an embodied carbon tool to select HVAC systems, assuming that such a tool could be made available during early building design. Interview

[1] A 'Category A' fit-out describes works undertaken by a developer for a commercial space prior to its occupation by tenants after the 'shell and core' works on a building are completed. Typically a Category A fit-out will 'extend central services onto floor plates and provide a background for Category B works' which offer a 'bespoke fit-out' for the tenant (BSRIA, 2011, p90).

participants were asked to comment on the type of information that might be useful, the form in which it should appear, the potential audience and anything else that might be needed to encourage use of the tool. Their comments, which are summarised in Table 6.3, are discussed in more detail in chapter 7, in which a specification for the tool is developed.

It is relevant here to note that several interview participants identified data on design parameters other than embodied carbon as a necessary aspect of the tool, as indicated by the contents of the 'type of data' column in Table 6.3. This reinforces findings of the industry survey outlined in chapter 4, in which features such as operational carbon and performance were consistently ranked as higher design priorities than embodied carbon. Similarly, the identification of building regulations as a necessary incentive by some participants to promote use of an embodied carbon selection tool for HVAC systems recalls the importance placed on building regulations in responses to the survey.

> *'…You'd have to make it law. It's not going to happen… People don't put PV on the roof because they think that they're saving the planet. They do that out of necessity despite how many Attenborough documentaries you watch that paint a more bleak picture about the work' (Participant P, 5 years in the industry).*

Table 6-3: Views of participants on user requirements for HVAC selection tool

Participant	Format of tool required	Type of data required	Likely audience	Incentives needed
A	N/A	Embodied carbon (EC) of HVAC components & systems	Entire design team	N/A
B	Excel spreadsheet or bespoke software	N/A	BREEAM or LEED assessors	BREEAM or LEED credits to promote EC
C	A look-up guide with a decision chart	EC data in a matrix alongside other choice criteria	MSEs and clients	Promotion by market-leading clients
E	Excel spreadsheet	EC data able to compare HVAC systems	N/A	N/A
F	Accessible, spreadsheet or software	EC and operational performance data for HVAC systems and components	Mechanical services engineers (MSEs), clients, architects	Publicity and a policy incentive, like BREEAM, Part L or the BCO guide
G	A plug-in to existing design software like IES	N/A	MSEs and clients	BREEAM credits, building regulations
H	Excel spreadsheet	EC data for HVAC components and systems	MSEs, clients, sustainability consultants	A section in the project specification
I	N/A	EC data	N/A	BREEAM credits, building regulations
J	Incorporation into CIBSE or BSRIA guides	N/A	Mainly MSEs	Promotion by industry bodies
K	Either a table or software	Both EC and OC data for systems and components	MSEs, clients, architects	BREEAM credits, internal promotion
L	N/A	High level EC comparison of HVAC systems	MSEs and clients	BREEAM credits, building regulations
M	Accessible, and with eventual inclusion in BIM	High level EC comparison of HVAC systems	MSEs, clients and contractors	Inclusion in building regulations
O	BIM model and web-based database	EC data on HVAC components, plus cost and performance data	MSEs and clients	BREEAM credits and inclusion in design contracts
P	A system compatible with SBEM / 'Part L'	N/A	Mainly MSEs	A legislative requirement to measure EC
Q	A quick reference guide, 'like CIBSE Guide F' with look-up tables	EC data on HVAC systems as well as cost data	MSEs and architects	Financial incentives or BREEAM credits
R	N/A	To be decided by manufacturer / supplier	MSEs and sustainability consultants	N/A

By contrast, voluntary incentives such as BREEAM or LEED credits were suggested by around half of interview participants although only a minority of survey participants had seen this route as helpful in persuading the industry to measure embodied carbon. The perception by participants that *'If you're trying to get to 'outstanding' in BREEAM, every little point counts'* (Participant F, 32 years in the industry) is supported by recent changes in BREEAM. The 2018 version of the 'BREEAM UK New Construction' scheme both raises the overall number of credits for conducting approved life cycle assessments and for the first time includes an exemplary credit for LCAs of 'core building services options during concept design' (BRE Global, 2018).

6.5 Discussion

6.5.1 Key features of decision-making

The findings of the qualitative study help explain key features about the practical context of decision-making on the choice of HVAC system and products for offices. Before considering emergent themes and theoretical issues, these findings can be summarised for the three topic areas addressed in the interviews, which were (a) definitions of HVAC systems, (b) decision-making on HVAC design; and (c) scope for reducing embodied carbon in HVAC design.

- **Definitions of HVAC systems:** Findings indicate that identifiable generic types of HVAC system exist, but there is no universally agreed classification of system types and decisions on choices of primary and secondary system may happen at different times in the timeline of building design. The interdependence of primary and secondary HVAC systems supports the need for the scope of embodied carbon estimation to include both of these for a given building.
- **Decision-making on HVAC design:** A clear group of factors including timing, spatial building constraints and prescriptiveness of a client brief appear to influence the extent to which HVAC design decisions draw on the advice of mechanical services designers. The degree of influence of the

designers on major design decisions such as the choice of HVAC system therefore varies between projects. Decisions on HVAC system choice also vary by the process used in each project, as do the preferences of different designers and their views on these processes.

- **Scope for reducing embodied carbon in HVAC design:** Scope exists for designers to make or influence decisions affecting the material efficiency and embodied carbon content of a chosen system in the appraisal of options for HVAC systems, the sizing, layout and material specification of components and the reuse of components on refurbishment and fit-out jobs. Alongside this scope, barriers exist to making decisions that might reduce embodied carbon in HVAC systems. These include a practical lack of information on embodied carbon impacts, the perception that these impacts are of low importance and standard practices influenced by rules of thumb that limit the choice of raw materials specified.

6.5.2 Themes associated with bounded rationality

Given these findings, how can decision support measures such as an embodied carbon selection tool be improved by theoretical insight into decision-making by practitioners? While decisions that involve comparing options against objective, scored criteria can in principle be made rationally if the required assumptions are in place, the rational choice model is easy to challenge as an explanation for all decisions on HVAC design. This is partly because the strict assumption of complete or perfect knowledge of all available options (Coleman and Fararo, 1992) is contradicted by the reported experience of designers. A second reason is that building design involves a project team likely to differ in their preferences and beliefs, whose actions may be affected by interaction between the group and other dynamic features of projects. Dynamic features of projects such as complexity and uncertainty have been found elsewhere to explain the use of satisficing by project managers at the start of projects (Williams and Samset, 2010). HVAC designers and construction clients also face complexity and uncertainty and may also use satisficing in decision-making.

A third challenge to rational choice arises because the advisory role of mechanical services designers within design teams means that their advice on HVAC options may need to reflect the preferences of others, particularly clients, besides their own preferences as technical experts. When asked what their ideal outcome was in approaching such decisions, several participants indicated that client satisfaction was the goal. For example: *'...because you might have put the best system in but the client's not happy with it for whatever reason, that doesn't count [for] anything'.* (Participant R, 40 years in industry). Designers therefore have to balance their definition of the 'best' system for the job with a choice that will satisfy the client, even if there is a difference between the two. In rational choice terms, this could mean that the choice that satisfies the client also prevents the maximisation of utility by the designer, therefore the designer could be said to face bounded rationality. A fourth challenge to rational choice is that cognitive factors influencing industry practice on raw material choice, oversizing and the perceived lack of importance attached to reducing embodied carbon and HVAC product reuse may all be indicative of bounded rationality.

In order to gain a better understanding of the approaches used by interview participants in forming or advising on decisions about HVAC design and inform decision support options, thematic analysis is used to identify whether the actions of designers, clients and other actors involved in decision-making could be understood using themes drawn from research literature. As discussed in section 2.7, rational choice theory is a prescriptive theory, therefore it lacks flexibility in explaining accounts by practitioners of decision-making in HVAC systems design. For a more effective explanation of the findings of this chapter, themes can instead be drawn from descriptive decision-making theories. As discussed in section 2.7, these theories argue that framing and heuristics are involved in human choice, that framing can precede or be part of the heuristics and that bounded rationality may be driven both by cognitive biases of actors and contextual constraints in the decision environment.

Depending on the theory used, the use of framing and heuristics in decision-making may either be seen as sources of cognitive bias (Tversky and Kahneman,

1974) or as ingredients in quick and effective decisions by experts (Hafenbradl et al, 2016, Klein, 2017). An understanding of heuristics, biases and framing used by practitioners can inform decision support measures by the use of choice architecture (Delgado and Shealy, 2018). As a qualification it should be noted that there is no universally accepted theory able to explain how human decisions combine analysis, whether rational or based on heuristics, with intuition (Hoffrage90 ,m. med and Marewski, 2015), therefore the use of descriptive theory here is only intended to indicate possible explanations of observed behaviour that may help to inform decision support.

6.5.2.1 Social heuristics

A study of decision-making by practitioners in the commercial building industry in the USA distinguished between 'judgmental' heuristics that inform individual decision-making and 'social' heuristics that reflect 'widely acknowledged and shared rules of thumb' in the industry (Beamish and Biggart, 2012, p 62). The social heuristics identified included a 'value added' heuristic expressed in decisions to choose building designs and technologies that were the most flexible, or suited to multiple users and tenants over the building life. This heuristic could help explain the finding that most participants in the present study said that clients for speculative office buildings overwhelmingly preferred fan coil unit systems, even if other HVAC systems might be better at meeting appraisal criteria on energy consumption, noise or maintenance costs.

> *'…Predominantly offices are built as 'spec' offices so the driver is flexibility. And that overrides pretty much everything else when it comes to spec offices because unless you can flog it to somebody there's no point in building it... the elements of carbon efficiency and the rest of it is there, but… it's kind of after the 'make sure this is flexible' type solution, so you end up with fan coil units'.* (Participant C, 20 years in industry).

The implications for decision support on embodied carbon estimation of a value added heuristic that restricts choice of HVAC systems are that more emphasis falls on estimating variations in embodied carbon impacts associated with system layout, sizing and raw material selection for the chosen system. As shown in section 6.4.2.5, these areas offer scope for reduction of embodied carbon impacts.

6.5.2.2 Recognition-primed decision-making

Where a client does not have a preference for a particular type of HVAC system and mechanical building services designers are able to influence the choice, individual designers may use judgmental heuristics. As shown earlier in sections 6.4.2.3 and 6.4.2.4, gaps in information or flaws in assessment metrics for comparing alternative HVAC systems can mean that choices are boundedly rational even if an option appraisal is used. In more critical situations, participants in the present study indicated that their advice on HVAC options was often needed for quick decisions during early building design before there was an opportunity to conduct an appraisal. One of several descriptive theories aiming to explain rapid decision-making by experts is Klein's 'recognition-primed decision' (RPD) model, a variant of naturalistic decision-making (Klein, 2017). It proposes that experts combine intuition and analysis to match cues in the decision environment to a repertoire of patterns in their experience and then mentally simulate the most appropriate courses of action without having to evaluate all possible options. A participant in the present study described how he used spatial features of the building and his experience to generate a list of possible HVAC systems:

> *'…It depends on the layout of the building and the depths of ceiling voids that you've got, the depths of raised floor that you've got. And so once you've got that information you'd start to build up a mental picture of really what you think you can start to physically engineer. Because the physical engineering is almost a challenge these days… you might say to them… well look there's three or four systems you could consider, you could consider VRV/VRF, you could consider chilled beams, passive or active with perimeter re-heat or chilled beams…'* (Participant N, 28 years in industry).

Applying the RPD theory to explain this example would suggest that expert mechanical services designers effectively narrow down the feasible HVAC options using a heuristic involving mental modelling. The implications for embodied carbon estimation are firstly that embodied carbon data on fewer HVAC systems might be needed to make comparisons because the heuristic would exclude options that are technically not feasible. Secondly, if generic embodied carbon benchmarks for HVAC systems were available, these could be used with the RPD method to provide a quick indication of technically feasible systems with the lowest embodied carbon impacts suitable for the project.

6.5.2.3 Status quo bias

As indicated in section 6.4.2.5, participants see 'standard practice' as the main influence on the choice of raw materials used in building services. Thus, '*the safest position'* for participants is *'to design the traditional'* (Participant L, 10 years in industry) rather than to specify components made from alternative materials with lower embodied carbon. The influence of standard practice may be explained by 'status quo bias' (SQB), or 'people's observed reluctance to change the status quo without good reason' (Beach and Connolly, p107). SQB has been used in research literature to explain the reluctance of building design teams to adopt non-traditional approaches to promote energy efficiency (Klotz, 2011). Examples of measures to address status quo bias in choice architecture include the award of credits for green design activities that depart from the status quo (Shealy and Klotz, 2015). This is supported by the suggestions of participants in this study for BREEAM credits and other incentives outlined in Table 6.3 to encourage the use of an embodied carbon tool for HVAC systems.

6.5.2.4 Framing and reframing

To what extent might the use of framing explain decisions on HVAC design and inform suitable measures to support decisions associated with estimation and reduction of embodied carbon? Firstly, the finding that embodied carbon reduction is not generally considered a priority in mainstream construction industry practice means its possible exclusion from frames of reference used by practitioners to approach decisions on HVAC system choice and the sizing, system layout and raw material specifications for a chosen system. Secondly, participants who described a policy to use the appraisal of HVAC system options as an opportunity to influence clients towards natural rather than mechanical ventilation were using a frame in which an outcome consistent with lower embodied carbon was prioritised. Thirdly, the findings on HVAC system layout and product reuse show that where design measures associated with environmental resource efficiency are framed in a context of cost savings, an outcome consistent with lower embodied carbon can also be prioritised.

The implications of these examples for decision support are as follows. To reframe embodied carbon reduction to have a higher priority in standard construction industry practice would entail clear communication of potential benefits of an embodied carbon estimation tool for HVAC systems to mechanical services designers, clients and wider design teams. Where the frame for decision-making on HVAC systems already includes a preference for natural ventilation, a strategy whose benefits include savings in operational energy consumption, an estimation tool could be used to quantify the value added in terms of embodied carbon savings. Lastly, the cost savings associated with design choices that have low embodied carbon might be included in the estimation tool as suggested by participants in Table 6.3.

Using the default assumption of rational choice in decision-making, an embodied carbon estimation tool for HVAC design would only need to provide complete and quantified information on the impact of a particular design choice at system or component level to enable the inclusion of embodied carbon as a design criterion. In practice, this may not be enough to achieve that result. By examining heuristics, biases and framing that may be used in decision-making by practitioners, a wider range of decision support measures covering user requirements as well as incentives to promote use of the tool can be identified. The measures are likely to include:

(a) Reframing of interventions that reduce embodied carbon to align with recognised strategies on materially efficient and less costly system design or the prioritisation of natural or mixed mode ventilation solutions that involve less material use;
(b) The provision of user-friendly estimation tools backed by data on embodied carbon impacts to support rationally-based HVAC option

appraisals such as the one in Table 6.2;

(c) Better communication of the range of possible design interventions that might reduce embodied carbon in building services as identified by CIBSE (2014a). This would include raising awareness on how interventions that might be considered non-traditional can attract BREAM credits, thereby providing an incentive to challenge status quo bias.

6.6 Chapter summary

A qualitative study of mechanical building services designers based in three UK regions has provided insight into the complexity of decision-making on the design of HVAC systems used in office buildings. The definition and boundaries of HVAC systems were clarified, indicating that although there is no definitive classification of systems, embodied carbon estimation should be inclusive of primary and secondary systems and decisions on system type may be staggered along a timeline for primary and secondary parts of the system. Several factors were identified that determine the extent to which mechanical building services designers may influence design decisions on each project. The processes used to make decisions on HVAC system type were found to vary by project between full option appraisals, discussions with clients and prescriptive choices led by clients of a single option. Scope for intervention to reduce embodied carbon by designers was identified in design decisions on the type, sizing and configuration of HVAC systems and components. The user requirements of designers for an embodied carbon selection tool were also documented.

The theories of rational choice and bounded rationality were considered as possible explanations for the processes used to make design decisions on HVAC systems and products. Of these, bounded rationality was more consistent with the processes described by participants. An examination of selected features of descriptive decision-making theories based on bounded rationality suggested that particular heuristics could be identified in the approaches of construction clients and designers to decision-making and a status quo bias could explain the relatively low perceived importance of embodied carbon within the construction industry. The use of framing was also found to provide a possible explanation for the inclusion or exclusion of embodied carbon as a consideration in decisions on HVAC design. Use of these theoretical topics to understand the findings of this study enables a wider range of decision support measures to be identified than those that would meet the needs of a decision maker under rational choice.

Overall, these findings suggest that mechanical building services designers retain considerable discretion to make or influence various decisions that are associated with reducing embodied carbon in HVAC design, even though the scope of their influence will vary based on timing of their involvement and the specificity of the client brief. Insight into choice theory can help target support for these interventions to match the decision-making processes used by practitioners, whether those processes are informed by rational choice, heuristics or bias.

What are the limitations of these findings? The main limitation is that, as with any studies based on a small sample, no claim can be made that the experiences of subjects and the inferences drawn from thematic analysis are typical or statistically representative of the parent population of mechanical building services designers in the UK. Also, the themes drawn from descriptive decision-making theory are employed with the qualification that there is no universally accepted theory able successfully to explain precisely how human decision-making combines elements of analysis, whether based on rational choice or heuristics, with intuition. However, as part of a sequential explanatory mixed methods research design, the findings of this chapter are able to complement and provide further insight into the findings of the survey presented in chapter 4, in which the sample was arguably representative of a wider group of UK construction industry practitioners involved with building services design.

Other limitations specific to this chapter as a mainly qualitative element in a mixed methods study are potential threats to validity around credibility, transferability and dependability. Measures taken to address each of these threats were outlined in Table 3.4 of chapter 3. Of these, transferability, which refers to whether the findings can have wider theoretical or practical applicability and usefulness (Ihantola and Kihn, 2011), is addressed in this chapter firstly by examining the findings against existing theory and applied studies on rational choice and bounded rationality. Secondly, the results of the theoretical analysis is directly applied to inform the user requirements of a decision support tool for practitioners, while the clarification provided on definitions and boundaries of HVAC systems is directly applied to inform an embodied carbon estimation method specific to those systems.

7 Specification for embodied carbon estimation tool

7.1 Introduction

This chapter draws on results from the previous chapters to develop a specification for a selection tool to compare HVAC systems by their embodied carbon impact. This is done using a framework of business requirements analysis (Paul et al, 2014), an approach that transforms social and technical information into a high level outline of business needs that can then be implemented in a software specification. A forward strategy is also outlined for the future development of the tool to encompass a wider range of building services and to draw on a larger evidence of case study data from building projects.

7.2 Methodology

Business requirements analysis, or business analysis, consists of five processes that are broadly equivalent to the preparatory stages of software development in the ISO standard for systems and software engineering, as shown in Table 7.1 (Paul et al, 2014, BSI, 2017). Its use is intended to be flexible in scope, to accommodate the needs or scale of the particular business or solution (Paul et al, 2104), just as the related ISO standard allows 'tailoring' of constituent processes in situations where full compliance is not appropriate (BSI, 2017). For the present study, this means that some processes are limited in scope or excluded where their outcomes have already been decided or fall outside the scope of the study. For example, the 'evaluate options' stage is limited in scope because the main option is defined by the existing project objective to 'produce a specification for a tool for practitioners to compare HVAC systems using embodied carbon'.

Table 7-1: Business analysis methodology

Business analysis process (Paul et al, 2014)	Examples of techniques (Paul et al, 2014)	Equivalent processes in ISO standards (BSI, 2017)
1. Investigate situation	Interviews, surveys, mind maps	Business or mission analysis
2. Consider perspectives	Stakeholder identification and analysis Business activity modelling	Stakeholder needs and requirements definition
3. Analyse needs	Gap or activity analysis Business process modelling	
4. Evaluate options	Cost-benefit analysis, risk analysis	N/A
5. Define requirements	Business process modelling Requirements elicitation IT systems modelling	System/software requirements analysis

7.3 Background investigation and consideration of perspectives

The main features of the business domain, situated internally and externally with respect to the project sponsor organisation are as follows. Externally, improved estimation of embodied carbon (EC) in the built environment meets an emerging global need arising from the rise in relative significance of EC compared to operational carbon (OC) emissions, following policy-led increases in energy efficiency (Ibn-Mohammed et al, 2013). A particular market gap exists around estimation of EC for building services systems, owing to a lack of suitable data or methodology (Passer et al, 2012, Birgisdottir et al, 2017). Some policy incentives now exist for inclusion of building services in EC assessments of buildings, such as an exemplary LCA credit under BREEAM (BRE Global, 2018). Internally, the project sponsor is a multi-disciplinary architectural, engineering and construction (AEC) consultancy whose strategic aims include the development of specific services around the circular economy as well as the provision of support on sustainable development issues to engineering teams (AECOM, 2016).

The identification of stakeholders and analysis of their roles was undertaken using a survey of 70 UK-based construction industry practitioners from a range of disciplines of whom 71% designed or specified building services (see chapter 4) and a qualitative study using interviews with 19 designers of mechanical building services based in four UK regions (see chapter 6). The four stakeholder groups identified in the qualitative study as potential users of the EC estimation tool were mechanical building services engineers (MSEs), construction clients, sustainability consultants and other design team members. Of these, MSEs and clients were also identified in the industry survey as stakeholders with most influence on whether building services were environmentally resource efficient. As the MSEs hold the lead responsibility for design decisions on HVAC systems, a business activity model shown in Figure 7.1 is used to describe their existing role within the business domain based on information provided within the qualitative study. Business activity modelling is a technique that visualises conceptual views from the perspective of one or many stakeholders on what a business does, using five categories of activity that are 'planning', 'enabling', 'doing', 'monitoring' and 'controlling' (Paul et al, 2014).

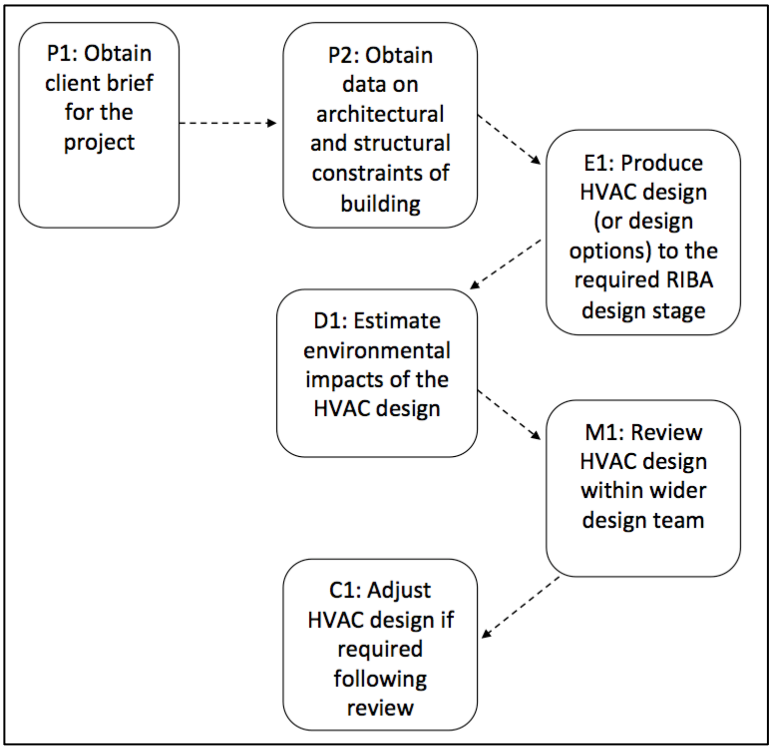

Figure 7-1: Business activity diagram

Key business activities in Figure 7.1 are categorised as planning (P1, P2), enabling (E1), doing (D1), monitoring (M1) and controlling (C1). The two main planning activities that influence the choice of HVAC system design and its associated embodied carbon impacts are the operational requirements in the client brief (P1) and the spatial constraints of the building (P2). This applies whether the project concerns a proposed (new) or existing building. Information generated by these activities supports the design of HVAC systems within the MEP (mechanical, electrical and public health) discipline to concept design stage, equivalent to RIBA stage 2 (RIBA, 2013), and to subsequent stages. Development of the design to a given design stage as required (E1) may enable estimation of likely environmental impacts to a corresponding level of detail, which is shown at D1. A concept stage design may include options for one or more types of HVAC system. The estimation of environmental impacts for the HVAC design (D1) is the area on which this study focuses and the broad activity within which EC estimation would need to happen. Data from interviews indicate that standard practice within D1 includes estimation of operational energy and carbon emissions, whilst EC estimation is far less common and if required may require outsourcing to external specialists. The estimation of impacts (D1) may happen at the concept, developed or technical stages of design, respectively denoted by RIBA design stages 2, 3 or 4 (RIBA, 2013). A design is then reviewed (M1) and if required, adjusted (C1) in the light of the results of D1. For projects involving more than one HVAC system option, M1 and C1 may also include the act of choice between options and the implementation of that choice. Activities affecting choice of HVAC designs that are performed by other design team members, such as economic cost appraisals of design options, also contribute to the monitoring and control activities M1 and C1.

7.4 Analysis of needs and definition of requirements

Analysis of the needs of stakeholders and definition of the requirements of a proposed information system are separate but inter-related processes, in that the latter follows, and is based on, the former (BSI, 2017, Paul et al, 2014). System requirements can include general, functional, technical and non-functional issues (Paul et al, 2014). Examples of general requirements include legal and policy matters while non-functional requirements include security and accessibility. For the present study, limitations in scope set by the objective of producing a high-level system specification mean that the focus of this section is on functional requirements, which relate to data entry, data processing and data retrieval. Technical requirements are out of scope as they relate to the development of a specific IT solution, as are accessibility requirements for the same reason. Based on the views of stakeholders identified in the qualitative study and listed in Table 6.3, the following statements of desired activities express needs that might be translated into functional requirements.

1. Estimation of the EC impact of a given type of HVAC system for which only the proposed building's net internal floor area (NIA) is known.
2. Estimation of the EC impact of a given type of HVAC system for which the proposed building's NIA, HVAC system type and details about some options for sizing or type of components are known.
3. Estimation of the EC impact of a bespoke HVAC design, for which all component choices will be made by the user (to include an HVAC system, part of an HVAC system, or one or more individual HVAC components).
4. Comparison of EC impacts of alternative HVAC systems or components.

Functional requirements based on these needs are identified and listed in Table 7.2. They address one additional need not discussed by stakeholders but forming a critical aspect of the estimation method developed in chapter 5, namely the need to include uncertainty analysis of estimated EC values, using first order analytical uncertainty propagation. Uncertainty analysis also supports the need to make comparisons of EC impacts, as it ensures that the comparison measures whether the difference between EC impacts of two options is statistically significant, as discussed earlier in sections 2.6.2.-2.6.3.

Table 7-2: Main functional requirements of system

Data input requirements	Data processing requirements	Data output requirements
Selection of type of estimate from menu - HVAC system level or bespoke. Input of amount of floor space to be served in m^2 of net internal area (NIA). Selection of HVAC system type from preset list of options. Selection and sizing of HVAC component type from preset list of options.	Calculation of EC impact of HVAC system based on preset inputs (nominal value and measure of dispersion) for component masses and carbon intensities and net floor space served. Calculation of EC impact of modified or bespoke HVAC design based on selected component sizes, types and preset inputs (nominal value and measure of dispersion) for component masses and carbon intensities.	Display of embodied carbon values and uncertainty range for selected HVAC system (in kg CO_2e total or kg CO_2e /m^2 of NIA). Display of embodied carbon values and uncertainty range for selected bespoke option(s) (in kg CO_2e total or kg CO_2e /m^2 of NIA). Comparison of impacts of alternative options.

A business process model of the functional requirements of the proposed estimation tool is shown in Figure 7.2. The model serves generally to describe a business process triggered by an event, within which are described process flows, tasks, decision points, actors and the outcome of the business process (Paul et al, 2014). Tasks are shown by rectangular boxes, decision points are shown by diamond shaped boxes and process flows are shown by arrows. The actors in Figure 7.2 are the user and the estimation tool itself. The event that triggers the process is the selection by the user of one of two kinds of estimate, while the outcome of the process is the display to the user of the EC impact of a selected option or multiple options for comparison.

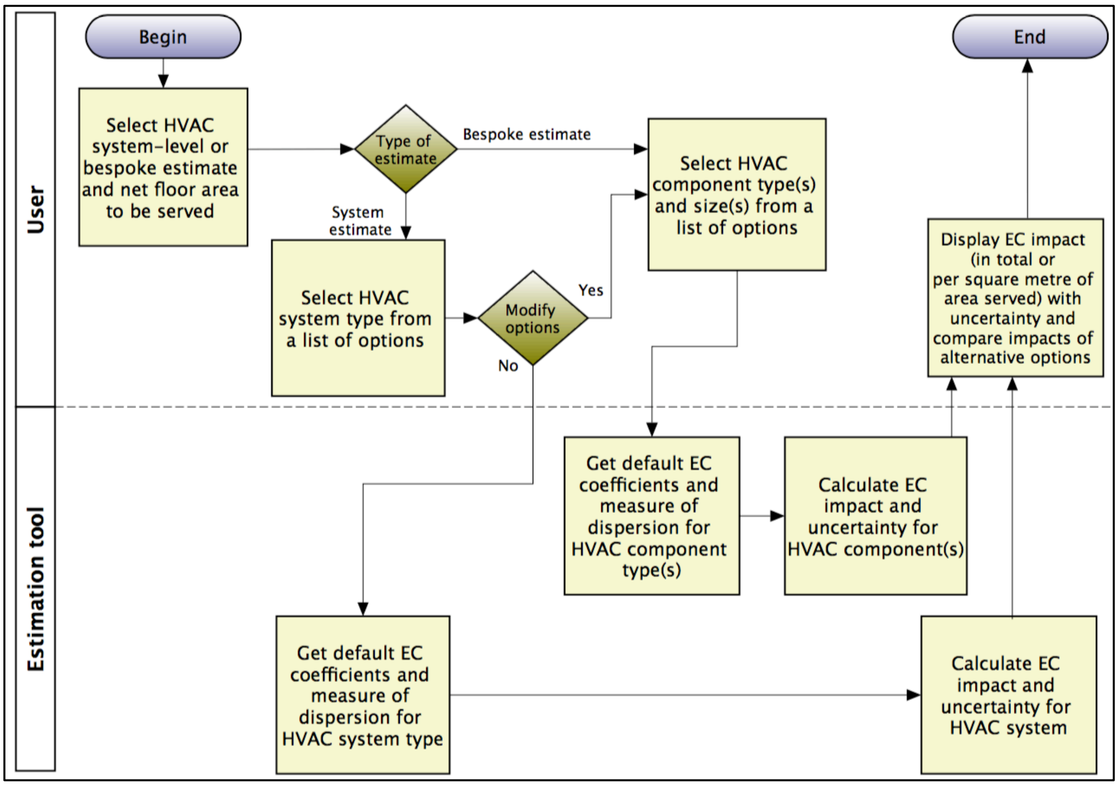

Figure 7-2: Business process model of proposed system

The data processing tasks shown in the bottom half of Figure 7.2 are implemented in a way that is demonstrated by the worked example in the next section.

A key implication of supporting bespoke design choices and uncertainty propagation is that the proposed system must be an automated tool rather than a manual look-up guide. This is because the complexity of calculations and range of possible results would be too great to encompass in a manual guide. The decision to design the specification to support an electronic solution is therefore an outcome of the 'evaluate options' process of the five-step business analysis.

7.5 Worked example

A user may select one of two types of estimate, a 'system estimate' and a 'bespoke estimate'. A key distinction between them is that in the first case, the user sizes the entire system approximately by providing a value of floor space, but does not size or select any individual components. In the second case the user can select and size some or all of the components. This means that in the first case, the estimation tool uses values for EC and uncertainty based on a default selection of component options for each type of HVAC system. In the second case the tool calculates EC and uncertainty for options that are either modified from the defaults or are entirely new, based on selections made by the user.

7.5.1 System estimate

In the first example, a user wishes to estimate and compare the respective EC impacts of a fan coil unit (FCU) system and a variable air volume (VAV) system for an office building with floor space of 5,000 m^2 NIA. The default values for each system, which are based on those of buildings 1 and 4 in section 5.4.5.4, would be generated by the system and are as follows:

- Mass of all components (m)
    - = 7.96 kg/m^2 (FCU); 13.09 kg/m^2 (VAV).
- Overall EC coefficient (k) for the product stages A1-A3 (BSI, 2011), (made up of the sum of the EC coefficients for raw material production, transport and manufacturing (=$k_R + k_T + k_{MF}$)).
    - = 2.46 kg CO_2e/kg mass (FCU); 1.81 kg CO_2e/kg mass (VAV).
- Nominal EC value of HVAC system (EC_{SYS})
    - = 19.61 kg CO_2e/m^2 (FCU); 23.69 kg CO_2e/m^2 (VAV).
- Uncertainty range U of ±2 standard deviations from the nominal value
    - = 17.31-21.91 kg CO_2e/m^2 (FCU); 20.06-27.32 kg CO_2e/m^2 (VAV).

The default values are obtained using Equation 7.1, in which the estimated EC value for each HVAC system EC_{SYS} is defined as the sum of the product of raw material masses m and EC coefficients k for raw material extraction k_R, transport k_T and manufacturing k_{MF}, plus or minus the error term U.

$$\mathrm{EC}_{SYS} = \sum_{i=1}^{n}[mk_R] + \sum_{i=1}^{n}[mk_T] + \sum_{i=1}^{n}[mk_{MF}] \pm U$$

(Equation 7.1)

The default, dimensionless values for EC_{SYS} of each system are therefore:

- 19.61 kg CO_2e/m^2 ± 2.30 kg CO_2e/m^2 (FCU system), and
- 23.69 kg CO_2e/m^2 ± 3.63 kg CO_2e/m^2 (VAV system).

The default value of the uncertainty term *U* for each HVAC system is obtained using a rearrangement of Equation 2.1.

$$U \approx \sqrt{\sum_{i=1}^{n} Var\ [x_i] \left[\frac{\partial y}{\partial x}\right]_{x_0}^{2}} \qquad \text{(Equation 7.2)}$$

In Equation 7.2, the standard deviation of output parameter *y* is approximately equal to the square root of the sum of contributions to variance of each input parameter x. In this case the input parameters are the values of *m* and *k* from equation 7.1.

The only new calculation performed by the tool in this example is to multiply these values by the size parameter for the floor area, the result being:

- EC_{SYS} = (19.61 kg CO_2e/m^2) * (5,000 m^2) = 98.06 tonnes CO_2e ± 11.51 tonnes CO_2e (FCU system), and
- EC_{SYS} = (23.69 kg CO_2e/m^2) * (5,000 m^2) = 118.45 tonnes CO_2e ± 18.16 tonnes CO_2e (VAV system).

By generating the values EC_{SYS} and *U* for each HVAC system, the EC tool supports a discernibility analysis, which is a comparison of whether significant differences exist between uncertain results for each HVAC system. In this case, significant differences do *not* exist between the results, i.e. nominal EC of the VAV system minus two standard deviations is less than nominal EC of the FCU system plus two standard deviations. If expressed in units of kg $CO2_e/m^2$, this means that:

- (23.69-3.63) < (19.61+2.30)

7.5.2 Bespoke estimate

In the second example the user wishes to compare EC impacts of two bespoke HVAC systems. For simplicity it is assumed that each system represents a modification of the default FCU system used in the first example for an office building with floor space of 5,000 m^2 NIA. The options are as follows:

- Option 1 - An alternative product choice for the air diffusers has an EC impact 80% lower than those used in the default FCU system.
- Option 2 - A less efficient spatial layout of distribution components requires 50% more ductwork and pipework than that of the default FCU system.

In this case, the tool would then apply new calculations using Equations 7.1 and 7.2 to modify the input parameters for mass in option 1 and EC in option 2. The modified values for each system option would be as follows:

- Mass of all components (m)
    - = 7.96 kg/m^2 (option 1); 9.14 kg/m^2 (option 2).
- Overall EC coefficient (k) for the product stages A1-A3
    - = 2.13 kg CO_2e/kg mass (option 1); 2.36 kg CO_2e/kg mass (option 2).
- Nominal EC value of HVAC system (EC_{SYS})
    - = 16.98 kg CO_2e/m^2 (option 1); 21.61 kg CO_2e/m^2 (option 2).
- Uncertainty range U of ±2 standard deviations from the nominal value
    - = 14.86-19.09 kg CO_2e/m^2 (option 1); 19.10-24.11 kg CO_2e/m^2 (option 2).
- EC_{SYS} = (16.98 kg CO_2e/m^2) * (5,000 m^2) = 84.90 tonnes kg CO_2e ± 10.57 tonnes kg CO_2e (option 1), and
- EC_{SYS} = (22.05 kg CO_2e/m^2) * (5,000 m^2) = 108.03 tonnes kg CO_2e ± 12.54 tonnes kg CO_2e (option 2).

Following the discernibility analysis the differences between options *are* significant, i.e. the nominal EC of option 2 minus two standard deviation exceeds the nominal EC of option 1 plus two standard deviations, or:

- (21.61-2.51) > (16.98+2.11)

Therefore option 1 would have a significantly lower EC impact than option 2.

7.6 Forward strategy

The forward strategy for the development of the specification includes three elements, which are as follows:

- Content development for existing functions: This entails further empirical measurement of HVAC components and systems to obtain more representative nominal values and measures of dispersion for masses. A schematic informing the strategy for this process is included in the next chapter at Figure 8.2. The process would first require widening the scope of HVAC component and system types covered and sample sizes. A second phase could include expanding the scope to cover components and systems from other building services disciplines.
- Technical implementation of existing functions via an iterative development model: This entails 'a cyclic process of prototyping, testing analysing and refining the requirements and the solution' (BSI, 2017, p18). This ensures that user feedback informs technical development but allows flexibility as to the form of prototype used (Paul et al, 2014). As this specification requires an automated implementation, user-facing prototypes could for instance be implemented using off-the-shelf software such as Microsoft Excel, which was the platform used to develop the underlying estimation method.
- Expansion of system requirements to accommodate other functional and non-functional area not previously in scope: The stakeholder needs identified in Table 6.3 include functionality to handle additional data and processing around operational carbon and economic cost along with suggestions about the format of a software tool. Both areas are

dependent on, and should follow, successful development of the first and second topics listed above.

7.7 Chapter summary

A specification was outlined for a tool for practitioners to compare HVAC systems based on their embodied carbon impacts. A framework of business requirements analysis was used to identify system requirements for an automated tool based on the estimation method developed in chapter 5 and the user needs identified in chapter 6. Based on these requirements, a business process model of the functions of the proposed system was outlined. The model enabled embodied carbon estimation at the concept, developed or technical design stages, corresponding to RIBA Plan of Work stages 2,3 and 4 (RIBA, 2013). Worked examples were presented of system calculations needed to support comparisons between embodied carbon impacts of HVAC systems, either based on default values or informed by bespoke choices of components made by users. A forward strategy was outlined for further development of the tool, which included expansion of available data content to cover a larger sample of HVAC systems and expansion of system requirements to include operational carbon emissions and cost.

8 Discussion and conclusions

8.1 Introduction

This chapter begins by reviewing the research problem addressed by this study . The implications of the findings for established theory and methodology are then discussed in relation to the primary topic, the embodied carbon estimation method incorporating uncertainty analysis and the secondary topic, the analysis of decision-making in HVAC design. After this the implications for practice are discussed. Finally, the contributions to knowledge are summarised.

8.2 Background to the study

The research objectives of this study were designed to support the overall aim of enabling a better understanding of the embodied carbon (EC) impacts of building services systems in commercial office buildings. The specific focus was on EC impacts during the 'product stage' of raw material extraction, transport and manufacturing, prior to building construction (BSI, 2011). The problem space was defined earlier in section 1.2 as one featuring uncertainty during the early stages of building design, both about the final design choices of materials and components and about the environmental impacts and economic costs of the final design. In addressing the uncertainty, established methods exist to estimate the impact of a given building services system on operational carbon emissions (OC). However, estimation of the EC impacts of such a system is more subject to uncertainty because of an apparent lack of suitable data, methods and tools. A second feature of the problem space is a lack of information on how and why particular building services design options are selected in practice, given that each option will have specific EC and other environmental impacts. This can be seen as another type of uncertainty. It is relevant to this study because improved knowledge of decision-making in building services design can help inform a decision support tool on EC of alternative design choices with the practical needs of practitioners responsible for making the decisions.

The research problem as described involved uncertainty about quantitative input parameters used to estimate embodied carbon as well as uncertainty about mechanisms of choice used by decision makers. The research design selected was therefore based on environmental life cycle assessment (LCA), a field based on physical science but influenced by the socio-technical context influencing the definition of problems that LCA studies are designed to address as well as the design and outcomes of LCA studies (as outlined in section 3.3.1). The research design was accordingly informed by two areas of theory, statistical theory for the investigation of uncertainty in EC estimation and choice theory for the investigation of decision-making in building services design.

8.3 Implications of findings for theory and methodology

This section reviews the theoretical and methodological aspects of the two main areas in which contributions have been made to knowledge, which are the embodied carbon estimation method and the analysis of decision-making in HVAC design.

8.3.1 Embodied carbon estimation

The estimation method developed in this study addresses a number of theoretical and methodological challenges identified from our analysis of previous research literature on embodied carbon (EC) analysis of the built environment. The first challenge is that building services systems are omitted from many LCA and EC studies of buildings owing to data gaps, as discussed earlier in sections 2.5.3, 2.5.4 and 2.5.6. The second challenge is the variability of methods possible within life cycle assessment (LCA) standards, a factor contributing to the uncertainty of reported embodied carbon values between research studies, as discussed in sections 2.5.2 and 2.6.2. The third challenge is that EC studies of buildings have been mainly deterministic in that they do not explicitly consider uncertainty, as discussed in section 2.6.2. The fourth challenge is a lack of guidance on achieving a balance between uncertainty reduction and uncertainty analysis, as discussed in section 2.6.1.

8.3.1.1 An estimation method focused on building services

The first challenge relates to a lack of available life cycle inventory (LCI) data, LCA studies and environmental product declarations (EPDs) on most building services components and systems. The focus of the present study on a major category of building services used in office buildings, HVAC systems, directly addresses this challenge with the development of a transparent method by which EC of generic HVAC systems and components can be estimated based on knowledge of input parameters. As discussed earlier in section 2.5.6, other parametric studies of embodied carbon in buildings have not offered sufficient transparency on the inventory calculations used for building services systems to enable the methods to be tested elsewhere. The second challenge concerns the contributory role of variations in methodologies adopted between research studies towards model and/or scenario uncertainty. To some extent, this issue is being addressed by recent research aimed at greater harmonisation of methodology (Birgisdottir et al, 2017). This study supports harmonisation by offering an estimation method that is transparent and reliable in that it can be replicated elsewhere.

8.3.1.2 Going beyond deterministic estimation

The third challenge concerns the prevalence of deterministic estimation methods in most embodied carbon (EC) studies of buildings. Besides the risk this poses for product comparisons (discussed in section 2.6.2), a deterministic EC analysis may understate the sensitivity of estimated EC for an entire building to the relative impact of EC of building services systems, by not considering 'uncertainty importance'. Uncertainty importance measures the relative contribution of uncertainty of a given input parameter towards total uncertainty of the result (Bjorklund, 2002). In this study, uncertainty importance is calculated by a contribution to variance (CTV) equation (Equation 5.2 in chapter 5), while total uncertainty of the estimated EC impact is shown graphically by an error bar representing a range of within plus or minus two standard deviations of that estimate, representing a 95.5% confidence interval. This means that if input parameters such as the masses or carbon intensities of raw materials used in building services are more uncertain than is the case for other building elements, building services will have a relatively greater impact on the uncertainty range of EC values for the whole building. This is demonstrated by the following example.

The average, product stage EC per square metre of gross floor area (GFA) in a study of 30 office buildings was 954.8 kg CO_2/m2, of which 13.3% was from building services, while the remainder was from other building elements, mainly consisting of the building structure and envelope, as shown in the first column of Figure 8.1 (AECOM, 2012). It is assumed that the relative uncertainty of each building element is set by a coefficient of variation (CV), the standard deviation of a random variable divided by its mean, of 10% for building services and 2.5% for all other building elements. The uncertainty importance of building services means that they are responsible for 27.5% of total variance of estimated EC for all building elements, which is over twice as large as their relative share of EC. The error bar in the first column represents the combined uncertainty of the result for all building elements, i.e. services, structure and other and its value represents ± 2 standard deviations away from mean EC of these elements.

It is now assumed that the estimated average value of EC of building services over a 50-year building lifetime is twice that of its value during the product stage, due to the effects of product replacement, or module B4 in the ISO LCA standards for buildings on building products (BSI, 2011, 2014). The assumed relative value for B4 is conservative in the context of research on recurring EC of building services (Birgisdottir and Rasmussen, 2016). For simplicity, recurring EC from other life cycle stages is excluded and carbon intensity of supply chains over the building lifetime is assumed not to change. The estimated average value of EC of all other building elements is assumed only to rise by 10% over the 50 years, as most raw materials in the building structure and envelope are not replaced. With the relative uncertainty of input data on each building element unchanged, building services now make up 21.9% of average EC of the sample of buildings, as shown in the right hand column of Figure 8.1. However building services now contribute over 55.7% to total variance of estimated EC for all building elements, which informs the length of the error bar attached to the right hand column. The uncertainty range of estimated EC for all building elements over 50 years, measured by a CV of 2.93%, is also 15% higher than its value for the product stage alone, which is 2.54%. This example shows that the uncertainty importance of building services as regards EC over the building lifetime can be greater than that of all other building elements. The estimated value of lifetime EC is therefore particularly sensitive to uncertainty of EC of building services.

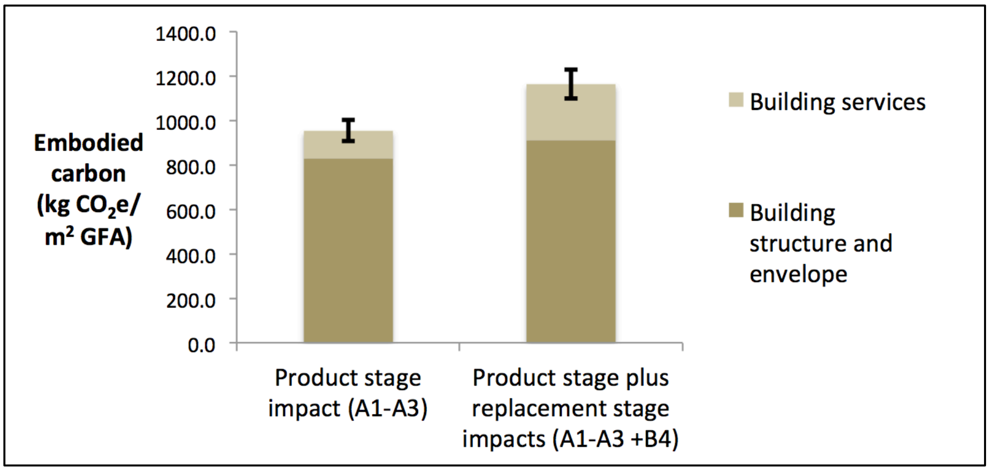

Figure 8-1: Uncertainty of estimated EC for 30 office buildings (AECOM, 2012)

8.3.1.3 Applying analytical uncertainty propagation

By focusing on parameter uncertainty within input data for building service systems, this study responds to the first and third challenges in embodied carbon research described in the previous section – the data gap on building services and the prevalence of deterministic studies that do not consider uncertainty. This is done using first-order analytical uncertainty propagation (AUP), an approach which was found in the literature review to have been used in one previous LCA study of the built environment (Hoxha et al, 2014), where it was applied to a case study of a small, residential building that did not include building services systems of the scale or complexity found in office buildings. The current study builds on and extends this approach by testing whether AUP can achieve comparable results to Monte Carlo simulation (MCS) but with greater computational efficiency. By applying this analysis to EC of HVAC systems in office buildings, an area that cannot be adequately investigated with deterministic methods, a method to inform early design decisions by practitioners to reduce EC in HVAC systems is enabled. Unlike the MCS method, which is normally only available within specialised LCA software, this approach is computationally simple and therefore suitable for inclusion within the simplest of tools, such as an Excel spreadsheet. The current study also highlights the fourth challenge identified above, of achieving a balance between contrasting strategies of uncertainty reduction and uncertainty incorporation. As discussed in the next section, it will be shown that while these strategies are often presented as alternatives (Heijungs and Huijbregts, 2004), they should be seen as complementary aspects of an LCA or EC study.

8.3.1.4 Breaking down parameter uncertainty

The treatment of uncertainty in LCA studies by strategies of reduction and inclusion was discussed earlier in section 2.6.1. Whilst it has been argued that of these, only inclusion via uncertainty analysis represents a formal approach (Beltran et al, 2018), the findings of this study indicate that uncertainty reduction is also a necessary part of LCA and EC studies of buildings, which at best can mitigate the risks of deterministic estimation. While uncertainty reduction via LCA standards or data quality matrices included in LCI databases may be unavoidable in embodied carbon studies of buildings, to achieve a balance between uncertainty reduction by empirical measurement and uncertainty inclusion using uncertainty analysis is not straightforward. If, following Walker (2003) and Kwakkel et al (2010), uncertainty is defined by its 'nature', its 'level' and its 'location', the nature of uncertainty is seen as a spectrum ranging from (a) ontic uncertainty, or inherent randomness, to (b) epistemic uncertainty associated with a lack of knowledge; and (c) uncertainty associated with ambiguity arising from multiple frames of reference. Of these types of uncertainty, it is argued by Kwakkel et al (2010) that only epistemic uncertainty can be reduced by additional measurement, although Morgan and Henrion (1990) also note that some variations observed in a quantity may appear inherently random because the pattern or model that might explain them is not yet known. Either way, probabilistic methods of uncertainty analysis can be used on parameter uncertainty that is either ontic or epistemic, provided that the level of uncertainty is 'statistical' or 'shallow', meaning it can be measured quantitatively on a ratio scale (Walker, 2003, Kwakkel et al, 2010). This can be illustrated by equation 7.1 from the previous chapter.

$$\mathrm{EC}_{cc} = \sum_{i=1}^{n}[mk_R] + \sum_{i=1}^{n}[mk_T] + \sum_{i=1}^{n}[mk_{MF}] \pm U$$

(Equation 7.1)

In equation 7.1, the error term U represents two standard deviations about the estimated value of product stage embodied carbon for a composite component EC_{cc}, which in turn is defined as the sum of the product of raw material masses m and embodied carbon coefficients k for raw material extraction k_R, transport k_T and manufacturing k_{MF}. If uncertainty propagation is used to quantify a value for U, as is the case in this study, uncertainty reduction by empirical measurement might lower the value of U by removing a part of U associated with a lack of knowledge. However, to measure the impact of such a reduction meaningfully also requires the use of uncertainty propagation, as the following example will show.

8.3.1.5 Combining uncertainty reduction with uncertainty analysis

Existing research sources discussed in section 2.5.6 and summarised in Table 2.3 show wide variations between reported EC values per square metre for building services systems in office buildings, of between 7.8 to 274 kg CO_2e/m^2. Possible reasons for the breadth of variation were discussed in section 2.5.6. To determine more precisely how much of this variation can be explained and how much is inherently random, or uncertain, we review the comparison made in chapter 5 between EC impacts of case studies of four alternative types of HVAC systems. Examples of variations found between HVAC systems and components are listed in Table 8.1, along with possible explanations and strategies to handle uncertainty.

The novel strategy used in this study is to distinguish variations that might be associated with differences between generic types of HVAC system or product (shown in rows 1 and 2 of Table 8.1) from those possibly associated with the uncertainty range of values for a single type (shown in rows 3-6 of Table 8.1). Successful classification of variations by type potentially reduces uncertainty if a distinct nominal value and uncertainty range can be associated with each type. For both kinds of variations, the next step is to obtain a wider sample of empirical measurements of raw material masses, if available. This provides inputs for an uncertainty analysis that yields a nominal value and a measure of dispersion for the EC of each generic type of HVAC product or system. Where a wider sample is not available, as was the case with the case study of HVAC systems, inputs are estimated using available data. In exceptional cases (shown in rows 7 and 8 of Table 8.1), uncertainty analysis may not be used. Instead, uncertainty is reduced by a normative decision to assume a consistent production process for a component type (row 7) or to use a particular empirical data source (row 8). Here the source of variation can be described as scenario uncertainty rather than parameter uncertainty. As this study focuses on parameter uncertainty, scenario uncertainty can be excluded from the uncertainty analysis as it arises from normative choices made by the researcher rather than uncertainty of input parameters within a given set of choices. A schematic of the strategy just described is shown in Figure 8.2.

Table 8-1: Examples of uncertainty analysis and uncertainty reduction

Type of variations	Values found	Possible explanations	Strategy
1. Variation between EC impacts of alternative types of HVAC system meeting the same functional equivalent criteria.	EC per m^2 of the VAV system is 1.2-2.2 times more than that of the FCU and VRF systems.	The VAV system is an all-air system with 2.9-4.6 times more ductwork per m^2 than the FCU and VRF systems.	Classify variations by type, empirical sampling to establish mass & EC range for each system, uncertainty analysis.
2. Variation between EC impacts per m^2 of the same type of HVAC system in two buildings due to different choices of equivalent products.	EC per m^2 of VRF system in building 3 exceeds that of the VRF system in building 2 by 40%.	Air diffusers used in building 3 have 3.4 times more EC than those in building 2 due to higher aluminum content.	
3. Variation between EC impacts per m^2 of alternative designs of the same HVAC system due to differences in spatial layout of each design.	Variations of up to 10% in mass and EC between possible HVAC designs estimated by interviewees.	Inherent variability exists between designers in the material efficiency of choices of HVAC system layouts.	Further empirical sampling to confirm uncertainty range, results used as inputs for uncertainty analysis.
4. Variation between EC impacts per m^2 of the same type of HVAC system designed for two buildings that differ in spatial layout or sizing.	EC per m^2 of the VRF system in building 3 exceeds that of the VRF system in building 2 by 35%.	Building 3 has 12% less floor space than building 2, so fewer economies of scale are possible in equipment sizing.	
5. Variations between EC impacts of alternative fan coil units of similar technical type, by size and rated power and by manufacturer.	EC per kg varies over size range by up to 4%. Mass varies by 35% between manufacturers.	Mass and rated power are the main determinants of EC for fan coil units.	
6. Variations between EC impacts of component data from manufacturers' bills of materials and that measured experimentally by tear-down analysis.	Fan coil unit mass measured by tear-down analysis is 6.3% above value in manufacturer's bill of materials.	Inherent variations exist between manufacturers' data and 'real' mass of raw materials within components.	
7. Variations between EC impacts of products associated with material waste in manufacturing.	EC per kg of fan coil unit varies by up to 12.6%.	Waste from steel casing and PUR foam insulation.	Assume same waste rate for all FCUs.
8. Variations between EC impacts of HVAC components specified by designer and those installed by contractor.	Extent of variation not yet measured.	Alterations often made to designed quantities and/or product choice by contractor.	Where possible, only use data from installed designs.

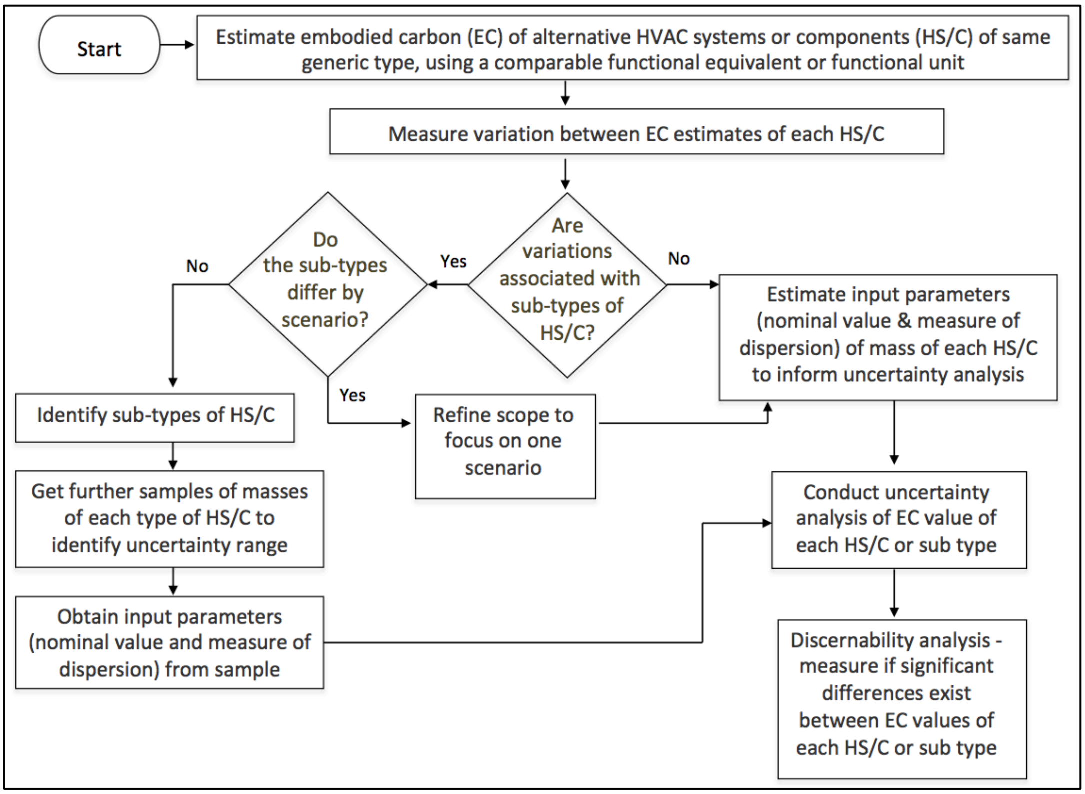

Figure 8-2: Strategy to inform uncertainty analysis and uncertainty reduction

The schematic in Figure 8.2 refers to handling of uncertainty in relation to raw material mass, which represents parameter *m* in equation 7.1, as this is the input parameter most influenced by gaps in data about the material composition of HVAC systems. However the uncertainty analysis can also include the parameters for the embodied carbon coefficients k_R, k_T and k_{MF} (relating to raw material production, transport and manufacturing) from Equation 7.1, as was done in chapter 5. Selection of input parameters to include in the analysis is also informed by the initial steps of contribution analysis and sensitivity analysis, as described in section 3.3.4.2.

Thus an iterative combination of empirical measurement and classification by type potentially reduces overall uncertainty found in the data, but it is only after uncertainty analysis that the reduction can be quantified in a meaningful way. In doing so, the advantage of using analytical uncertainty propagation over Monte Carlo simulation is that even if a full probability distribution is not available for the input values, only a nominal value and measure of dispersion are needed (Heijungs and Lenzen, 2014). This approach is novel in that it provides a guideline on the scope and sequencing of uncertainty analysis within an EC study, for a building element, the building services system, about which there are substantial gaps in data on raw material type and mass.

8.3.2 Decision-making in building services design

What are the implications of the findings on decision-making in HVAC design? The findings of chapter 6 challenge the notion that practitioners make decisions based on optimisation of rational alternatives. Yet as discussed in section 2.7, the dominant approach of research literature on HVAC design has been to use multi-criteria decision-making (MCDM), a field in which most studies seem to be informed implicitly by the assumptions of rational choice. Some research on environmental decision-making outside the topic of HVAC design has combined MCDM with prospect theory (Gomes and Lima 1991, Qin et al, 2017), in models that address bounded rationality to the extent that information about choice options is seen as imperfect and framing may influence preferences. However, prospect theory is based on a 'gambling' approach to choice in which efforts by decision makers to subvert choice mechanisms are not recognised (Beach and Connolly, 2005, p90-91). This theory would not explain the deliberate weighting by designers of HVAC option appraisals to support a preferred choice, a feature described by interview participants in section 6.4.2.2.

In the light of the empirical findings on decision making in this study, the discussion in sections 6.5.2 – 6.5.2.4 uses areas of descriptive decision theory not previously applied to HVAC design. These are based on bounded rationality but also accept emotional and/or intuitive motivations for behaviour by decision makers. For instance, 'social' heuristics help explain the preferences of construction clients for particular HVAC systems and a 'status quo bias' helps explain an industry preference for using 'standard' raw materials rather than low carbon alternatives The ability of expert designers to use heuristics to help make critical decisions during early building design may also be explained by a 'recognition primed decision' model.

Unlike earlier research on decision-making in HVAC system design, the findings of this study refute the position that a single model can explain the range of behaviours identified by practitioners in this area and map the mechanism needed to support better decisions. Instead it is posited that decision makers will behave rationally in some circumstances but various factors associated with bounded rationality, including imperfect information and emotional bias, often prevent them doing so. The interaction of those factors with rational behaviour is uncertain and difficult to predict. Decision support measures aimed at reducing EC impacts of HVAC systems should therefore be able firstly to quantify the impacts and related parameter uncertainty to inform measurable decision criteria. Secondly, they also should include incentives aimed at 'debiasing' the decision maker (Montibeller and von Winterfeldt, 2015), to address uncertainty about decision-making processes. 'Uncertainty about decision-making', used in this sense, does not mean 'scenario' uncertainty or 'uncertainty about choices' which are expressions discussed in section 2.6.1 that describe uncertainty about the normative choices made in setting boundaries for an LCA study. Instead it refers to uncertainty about the extent to which decision-making processes depart from the classical rational choice model. Using this definition, the most uncertain decision-making process is one in which no amount of information about utility functions or measurable decision criteria can predict the outcome of a decision.

It is further suggested that parameter uncertainty within embodied carbon estimation may even influence uncertainty about decision making in building services design. Assuming that a process of framing informs decision-making on environmental issues in construction (Delgado and Shealy, 2018) and a 'pre-environmentalist' frame of reference exists in which nature is seen as self-correcting, then uncertain environmental impacts may be seen as unproven and a reason not to take action (Bras-Klapwijk, 1998).
A well-documented example of the use of scientific uncertainty about environmental impacts to justify inaction is climate change denial (Lewandowsky et al, 2015). Therefore a high level of quantitative uncertainty about EC impacts of building services may partly explain the low or non-existent

profile of EC as a priority within the frame used by practitioners to inform design decisions. This has not been identified in existing studies of barriers to embodied reduction in construction (e.g. Giesekam et al, 2016), but it is worthy of consideration alongside other documented barriers.

8.4 Implications of findings for practice

This section reviews the implications of the findings for practical knowledge on embodied carbon reduction, building information modelling (BIM) and building services design.

8.4.1 Embodied carbon reduction

Recent research literature on practical interventions to reduce embodied carbon based on 80 international building-level case studies has quantified the reduction potential of various strategies that include product substitution, increased material efficiency of design and product reuse (Malmqvist et al, 2018). The strategies were summarised earlier in section 2.8. While almost all of the case studies examine EC reductions with respect to structural building materials, relatively few measure their effects on building services systems (Birgisdottir et al, 2017). The present study contributes to this area of practical knowledge by providing detail on the relative effectiveness of established strategies of EC reduction when applied to building services systems.

For instance, the variation by a factor of 1.2 to 2.2 in product stage EC impacts between alternative HVAC systems shown in Table 8.1 can be contrasted with smaller reductions of between 15 and 77% in product stage EC that were found in other case studies to be associated with replacing concrete with timber in structural systems (Malmqvist et al, 2018). Conversely, variations in EC of up to 10% between alternative spatial layouts for the same HVAC system are shown in Table 8.1. These values are comparable in magnitude with the EC reduction for structural materials of 6% found in a case study to be associated with changing building form from rectangular to square (Malmqvist et al, 2018). Although the values in Table 8.1 are only indicative and should ideally be based on more extensive empirical sampling, the results of this study widen the scope for investigation of embodied carbon reduction, thereby enhancing knowledge in this area.

8.4.2 Embodied carbon estimation tools

The practical ability to quantify possible reductions in embodied carbon associated with product substitution, material efficiency of design and other mitigation strategies is also implemented by the specification for an estimation tool designed for practitioners, as outlined in chapter 7. The fact that the specification is platform-independent can also address the challenge of leveraging the benefits of building information modelling (BIM) for embodied carbon estimation of building services, a topic discussed in section 2.5.8.

The limitations of BIM as a source of life cycle inventory data were illustrated in chapter 5 in the sense that only one of the four case studies of HVAC systems was able to draw on material data from a BIM model produced by the design team. This BIM model contained raw material data for ductwork and pipework made of single materials but not for terminal units or rooftop condensers, which are 'composite' components, made of multiple raw materials. This highlights the challenge discussed in section 2.5.8 that current BIM standards omit a vital layer of detail, concerning the types and masses of raw materials needed to support calculation by BIM users of embodied carbon (EC) for composite components. Without this layer, EC values must be calculated separately via a bespoke LCA study or environmental product declaration (EPD) for a single product, or estimated for a generic class of products by a parametric method not dependent on data from the BIM model, as proposed by this study. As the cost of producing an EPD falls upon the product manufacturer, a parametric method of EC estimation may offer a more practical solution.

This study therefore argues that further work is needed to develop the potential of BIM in measurement and reduction of whole-life carbon emissions. Ideally, a ‘smart’ BIM object representing a building services component might hold details on a variety of whole-life environmental impacts that could be updated during the building life (Wong and Zhou, 2015). As noted earlier, there appears to be little enthusiasm in the construction industry for the inclusion of complete details of raw materials in the BIM representations of composite building services components. The estimation method developed by this study therefore provides an alternative route by which data on EC values of these components could be generated off-line for subsequent inclusion in BIM.

8.4.3 Decision-making in building services design

The objectives of this study include the production of a specification for a decision support tool, but not an implementation of such a tool. Therefore the practical implications of the study on decision-making relate more to insight into barriers and enabling features around decisions on embodied carbon (EC) reduction in building services. While the preceding chapter focused on the functional features required by an EC estimation tool for HVAC design, this section takes a broader view of enabling features, drawing on the results of the industry survey as well as the qualitative study.

Depending on the theoretical or methodological perspective through which the practical barriers are viewed, particular enabling features may appear as appropriate solutions. For instance, a focus on psychological biases that might hinder positive environmental choices informs passive intervention via the use of framing in ‘choice architecture’ (Delgado and Shealy, 2018). A focus on measuring the extent to which building environmental assessment (BEA) schemes reward EC reduction informs active intervention by raising the share of credits available (Ng et al, 2013a). The findings of this study indicate that both active and passive interventions can incentivise EC reduction in building services whilst adding to an understanding of the way practitioners might respond. Interventions that might reduce EC are seen as less important by survey respondents when framed as criteria for specifying building services than when framed as general aspirational goals (see section 4.4.5). This suggests that practitioners accept why EC reduction should be an environmental goal but find it hard to link it with their existing work practices. This may also explain the survey finding that less familiar interventions such as product reuse and reducing consumption of scarce materials attract lower levels of buy-in from practitioners than more familiar ones within current work practices, such as reducing operational energy and carbon emissions. Equally, the need identified by participants in the qualitative study to include data on operational carbon emissions and costs in an EC estimation tool can be seen as a way to link an unfamiliar intervention to one that forms part of existing practice. The inclusion of this data in such a tool could be seen as a way to reframe EC reduction to counteract the status quo bias identified in section 6.5.2.3 that might exist towards integrated design approaches to whole-life carbon impacts.

8.5 Summary of contributions to knowledge

The main contributions to knowledge are summarised as follows:

8.5.1 Contributions to theory and methodology

This study firstly develops a parametric method to estimate product stage embodied carbon in building services systems, theoretically based on environmental life cycle assessment and implemented via empirical case studies of heating, ventilation and air-conditioning (HVAC) systems and components. The method is novel in that it includes:

- A focus on two areas largely unexplored by previous research on embodied carbon in the built environment, building services systems and uncertainty analysis;
- A method that is transparent and replicable across building services systems for which data on raw material type and mass is scarce, using an iterative combination of uncertainty reduction and uncertainty analysis;
- The application of first-order analytical uncertainty propagation (AUP) and its testing against Monte Carlo sampling to provide a computationally

efficient method suitable for use within embodied carbon assessments of building services systems during early building design;

This study also provides an analysis of decision-making in the design of HVAC systems, drawing on a qualitative study of practitioners and informed by a comparison of alternative theories of rational choice-based and descriptive decision-making theories based on bounded rationality. Key features include the following:

- The finding that decision-making by practitioners exhibits features that may at times be explained by rational choice or descriptive theory, but the interaction between classically rational and boundedly rational behaviour in each decision-making environment is inherently uncertain. This contrasts with the prevailing approach in research studies on decision-making in HVAC design, that are informed by multi-criteria decision-making (MCDM).
- The finding that the use of framing may inform the relatively low priority given to embodied carbon by building services designers as well as the design of decision support measures aimed at reduction of embodied carbon in building services.

8.5.2 Contributions to practical knowledge

- The focus of the embodied carbon estimation method on building services systems enables measurement of the comparative effectiveness of established strategies of embodied carbon reduction usually applied to structural building materials, while the inclusion of the estimation method in a specification for a decision support tool informs a practical application of the method aimed at HVAC design practitioners.
- Analysis of the role of building information modelling (BIM) as a source for life cycle inventory input data shows that ISO standards and industry practice do not require a sufficient level of raw material detail to support embodied carbon analysis of composite components within BIM. This suggests that 'off-line' embodied carbon estimation methods such as that

developed by this study are needed to support the inclusion of embodied carbon values for building services systems in BIM models.

- The industry survey and qualitative study of decision-making together identify a range of practical barriers and enabling features associated with embodied carbon reduction in building services design. While support measures vary according to the conceptual approach used to identify barriers, a range of interventions informed by multiple approaches are found to be potentially useful to incentivise change.

8.6 Conclusions

This section begins by identifying key findings in relation to the research aim and objectives and related research questions. Limitations of the study are then discussed together with alternative approaches that may have been used, after which recommendations for further work are made in relation to the study as a whole. The overall aim of the study was to 'investigate and enable a better understanding of the embodied carbon impacts of building services systems in commercial office buildings and the effects of uncertainty on estimation of those impacts'. This was achieved by meeting five research objectives, each of which is now discussed.

8.6.1 Research objective RO1

To identify a range of barriers and drivers that inform industry practice on the calculation and reduction of embodied carbon in building services systems.

To meet the first research objective, the related research question asked what were the determinants for decisions by construction industry stakeholders to measure and take action to reduce embodied carbon in those systems. The results presented in chapter 4 documented perceptions of industry practitioners about embodied carbon and other topics associated with the measurement and improvement of environmental resource efficiency. Broad support was identified for resource efficient practices alongside insight into specific barriers and opportunities and mixed views about the effectiveness of various interventions and incentives to promote their use.

The findings suggest that the barriers identified in the survey are not seen as insurmountable by respondents if certain interventions are made to drive change. For instance, attitudinal barriers to embodied carbon reduction in building services might be countered by 'hard' policy incentives such as the use of building regulations. Alternatively, more passive incentives could promote awareness that features such as greater product durability and service life have embodied carbon benefits. Gaps in knowledge about the existence of environmental product declarations (EPDs) could be countered by better communication about their availability and benefits. Technical barriers such as concerns on the quality of data and embodied carbon estimation tools might be addressed by work such as the tool proposed by this research study if developed in accordance with the forward strategy in section 7.6. These barriers may also be bypassed by a focus on early design decisions to lower the overall level of servicing in a building, but the carbon savings must still be quantifiable. The estimation method developed in chapter 5 and the specification for an estimation tool developed in chapter 7 use uncertainty analysis to address gaps in quantity and quality of input data and are therefore designed to support early design decisions by the use of system-level or bespoke estimates.

The survey findings inform other research objectives of this study. Firstly they help define the goal and scope of the LCA-based embodied carbon analysis used to develop the estimation method to meet the research objectives RO2 and RO3. This is enabled by the confirmation by survey findings that a method able to estimate product stage embodied carbon of building services systems has relevance to practitioners. For instance, a majority of practitioners would find an embodied carbon estimation tool useful in their work and their comments indicate that it would have particular benefits for certain clients. Secondly, the findings are used to identify topics related to decision-making by heating, ventilation and air-conditioning (HVAC) designers for further exploration in the qualitative study that is the subject of research objective RO4. Thirdly, the views of survey respondents inform the requirements analysis for the specification developed for an embodied carbon estimation tool, to meet research objective RO5. They indicate, for instance, that while data quality and software maintainability might be challenges, the effectiveness could be enhanced by integration with analysis of economic cost and/or operational carbon emissions.

8.6.2 Research objectives RO2 and RO3

To develop an estimation method for embodied carbon of composite building services components that addresses uncertainty of input parameters (RO2).

To apply the estimation method to the comparison of embodied carbon impacts of alternative mechanical services systems, initially focusing on heating, ventilation and air-conditioning (HVAC) systems (RO3).

The second and third research objectives related to the development of an embodied carbon estimation method suitable for building services components and systems in which an analytical method of uncertainty analysis was included. The related research questions RO2 and RO3 asked whether a suitable parametric estimation method could be developed, how uncertainty of input parameters would affect its results and whether such a method could be used to compare alternative HVAC systems. Results of the investigation were presented in chapter 5 using empirical case studies of HVAC components and systems. These demonstrated that the parametric estimation method was feasible if applied to generic, composite components, using the example of fan coil units. In one sense, this method provides a protocol by which LCA results for a single composite HVAC component can be extended to apply to the generic class of components to which that component belongs. As indicated in section 8.4.2, this could provide an 'off-line' layer of calculation that would generate embodied carbon data to be stored within building information modeling (BIM) objects representing composite building services components.

When the parametric method was combined with first order analytical uncertainty propagation (AUP), values for output uncertainty were not significantly different from those obtained using Monte Carlo Simulation (MCS). The greater computational efficiency of AUP makes it suitable for integration into simple tools, such as Excel spreadsheets, which could be used by building services designers without requiring the level of expertise needed to run MCS simulations within specialised (and expensive) commercial LCA software.

The method was shown to support comparisons of embodied impacts of equivalent HVAC components and building level HVAC systems and identification of whether differences between systems were statistically significant. In principle this represents a vast improvement over the use of simplified, deterministic embodied carbon assessment methods (RICS, 2010, 2014, 2017). Such methods may suggest that two choices of a product system have 'different' embodied carbon values without a robust basis for doing so because they ignore parameter uncertainty. The added value that the estimation method developed by this study might bring to the analysis of whole-life carbon impacts was shown by its application to a comparison of operational and embodied impacts of three fan coil units over a 10-year service life. Sensitivity analysis helped to emphasise the point that use of alternative LCI databases did not hinder the ability of the estimation method to make comparisons between alternative types of HVAC system.

Overall, the method was shown to be able in principle to support comparisons of alternative HVAC design options during early building design when detailed data on component choice would not yet be known. In its simplest form, the method provides default values for product stage embodied carbon and uncertainty for alternative generic types of HVAC system, expressed in relation to a square metre of net internal floor area. The method also is scalable in that it can produce increasingly bespoke EC estimates as more information on design choice becomes available. The method includes a structured protocol for widening the empirical sample sizes and ranges of component types that inform the default values. This is implemented using an iterative approach, as described in section 8.3.1.5. Novel theoretical and methodological features of the embodied carbon estimation method were summarised in section 8.5.1.

The development of the EC estimation method in chapter 5 also informs the specification for an estimation tool developed to meet research objective RO5.

8.6.3 Research objective RO4

To identify and explain the decision-making processes involved in selecting options for the design of HVAC systems for office buildings.

The fourth research objective (RO4) entailed identification of decision-making processes used in the design and selection of HVAC systems for UK office buildings. The associated research question RQ4 asked how and why particular design options were selected. The findings of the qualitative study presented in chapter 6 defined key factors informing the extent to which designers may influence design decisions on an HVAC design project. Decision-making processes were found to vary between projects and between designers, while scope for intervention during design to reduce embodied carbon was identified in decisions on the type, sizing and configuration of HVAC systems and components. Theories of rational choice and bounded rationality were examined as lenses through which to clarify possible explanations. Of these, some aspects of theories based on bounded rationality were particularly able to explain decision-making activities of HVAC designers and construction clients and industry attitudes to embodied carbon. These included the use by practitioners of heuristics that might alternately help or hinder effective decisions, a 'status quo' bias and a use of 'framing' in approaching decisions that might either support or hinder decisions associated with reducing embodied carbon. The analysis also showed that the interaction between rational and boundedly rational behaviour by practitioners in a given decision context was uncertain. This suggests that decision support measures should be targeted to address both types of behaviour.

Overall, the findings of chapter 6 suggest that mechanical building services designers retain considerable discretion over decisions that are associated with reducing embodied carbon in HVAC design, although the scope of their influence will vary based on timing of their involvement and the specificity of the client brief. Insight into choice theory can help target support for these interventions to match the decision-making processes used by practitioners. Examples outlined in section 6.5.2.4 include (a) 'reframing' of interventions that reduce embodied carbon to align with recognised design strategies; (b) better communication of the range of possible design interventions to reduce embodied carbon as identified by CIBSE (2014a) and the policy incentives for doing so; and (c) the provision of estimation tools appropriate for the concept stage of building design to support rationally-based HVAC option appraisals.

The findings of the qualitative study also enabled an understanding of user requirements and the definitions and types of HVAC system required to develop the specification for an estimation tool required by the fifth research objective. While choice from a client perspective often focuses on the choice of secondary HVAC systems, the interdependence of primary and secondary systems makes it essential that both systems are included within the scope of the estimation tool. The user requirements expressed by qualitative study participants reinforce some of the findings of the industry survey outlined in section 4.4.7. This, for instance, includes a preference for integration of the tool with assessment of operational carbon emissions and/or cost as well as support for hard incentives such as building regulations or BREEAM credits to increase take-up. Beyond this, views expressed in the qualitative study indicate that the tool would need to support high-level comparisons between HVAC systems by type as well as detailed comparisons of bespoke choices of components for a given system.

8.6.4 Research objective RO5

To produce a specification for a tool for practitioners to compare HVAC systems using embodied carbon.

The fifth research objective (RO5) required the development of a specification for a tool for practitioners to compare HVAC systems based on their embodied carbon impacts. The associated research question RQ5 asked what the technical and user requirements were of such a tool. The specification was outlined in chapter 7, along with a forward strategy for further development of the tool. As the required functionality would require an automated tool, a business process model of the functions of the proposed system was outlined, based on system requirements drawn from the estimation method developed in chapter 5 and the user needs identified in chapters 4 and 6. Worked examples were presented of the calculations that would need to be performed by the system to support comparisons between embodied carbon (EC) impacts of HVAC systems, either based on default values or informed by bespoke choices of components made by users. A forward strategy was outlined for further development of the tool, key elements of which were expansion of available data content to cover a larger sample of HVAC systems both by number and by type and an expansion of system requirements to include operational carbon emissions and cost.

There are several implications of a tool or tools that could be developed based on this specification. Firstly, the tool would address the practical challenge identified in section 1.2, such that the raw material profiles of generic types of composite component or technical systems of building services are typically unknown. The parametric method used by the tool to generate EC estimates could be informed by an evolving database of these profiles. Secondly, the tool would support key strategies of EC reduction by (a) substitution of alternative HVAC components or systems, (b) increasing the material efficiency of a given design, or (c) product reuse. Thirdly, as discussed in section 8.4.2, the tool could generate EC values for composite components for subsequent inclusion within BIM models, after which EC values of alternative design scenarios could be generated within the model. In principle, the BIM object representing such a component could include fields representing not only its nominal EC value but also the measures of dispersion representing the uncertainty of its mass m and EC coefficient k. If this were done, the AUP equation would need to be implemented within the BIM software, possibly by an add-on module, in order to calculate output uncertainty of the total EC value of a given design scenario.

8.6.5 Limitations of the study

This section considers limitations that may influence the extent to which findings have been able to address the research questions, either due to the choice of research design or to practical issues arising in collection of data. A brief discussion follows on alternative methods that might have been used to address key research questions and their possible implications.

8.6.5.1 Threats to validity

The threats to validity of using the mixed methods research (MMR) approach within this study and measures taken to mitigate these threats, including integration of findings during data collection and analysis, were discussed generally in section 3.6 and in relation to specific findings in sections 4.5.5, 5.5.2 and 6.6. The mitigation strategy combined established approaches to handle aspects of the study in which quantitative and qualitative methods were not mixed and the use of a 'legitimation' approach (Onwuegbuzie and Johnson, 2006) to define and address threats specifically around integration of quantitative and qualitative material. To address these threats, qualitative data was collected and analysed in such a way as to complement, develop or expand on the largely quantitative embodied carbon estimation method. For instance, the analysis of system requirements for a practitioner-facing estimation tool in chapter 7 integrated the quantitative estimation method with qualitative data on user needs using the framework of business requirements analysis (Paul et al, 2014). Similarly, findings of chapters 4, 5 and 6 were integrated as part of the analysis in the discussion within chapter 8..

Given the centrality to this research of the embodied carbon estimation method developed in chapter 5, the most critical threat to validity is arguably whether the sample of HVAC components and systems used for case studies was sufficiently representative to support external validity of the findings. To explore this question, the next section examines practical challenges in data collection.

8.6.5.2 Practical challenges in data collection

Insofar as the main focus of this study was the development of an embodied carbon estimation method as required by research objective RO2, it is in this area that practical challenges around data collection had most impact. It was originally intended to obtain detailed empirical data for at least three types of generic, composite HVAC components to complement the study of fan coil units. Contacts were made via the project sponsor and industry trade associations with manufacturers of VRF systems, modular condenser boilers and air-cooled chillers and discussions took place to encourage participation. These components were selected because, as with fan coil units, they were known to be widely used in office HVAC systems and to be based on standard technologies for which raw materials were relatively consistent between manufacturers. In practice it was only possible to obtain input data for a few individual models of chiller rather than any complete ranges, as some manufacturers were unwilling to release data because of concerns about confidentiality. This meant that it was not possible to re-test the hypothesis based on a previous study (Riviere et al, 2012) that the embodied carbon relative to mass of chillers or boilers would vary inversely with the size and power of the unit across the available range, as was found to be the case with fan coil units in chapter 5 of this study.

While further research in this area would be valuable, the parametric estimation method does not rely on this hypothesis, as it is based instead on the findings of section 5.4.1-5.4.2. These findings support a broader hypothesis that mass and rated power are the most likely determinants of embodied carbon for an electrically powered, composite HVAC component made with consistent raw materials across its available size and power range. This builds on an idea posed by earlier research that rated power could be a 'defining metric' for estimating embodied carbon of components such as boilers and pumps (Moncaster and Symons, 2013). Ultimately, both hypotheses depend on the two-part premise that (a) product stage embodied carbon is known to vary proportionately with the mass of a raw material and (b) it can be reasonably assumed that generic, composite components are likely to be made of consistent proportions of specific raw materials. Further empirical research on other composite HVAC components would clearly strengthen the external validity of the estimation method but would arguably be unlikely to contradict this premise.

To address research objective RO3, the EC estimation method was extended to focus on HVAC systems. The initial aim was to take off quantities from designs of the five most common HVAC systems installed in UK office buildings with over 1000 m^2 in floor space. The most common systems were defined by the perceptions of mechanical services engineers interviewed, which were found broadly to confirm those of previous research in section 6.4.1. Besides systems using fan coil unit, variable refrigerant volume and variable air volume technologies, this would have included systems using chilled beams and displacement ventilation (DV). However, while MEP designs from recent projects with all five types of HVAC system were obtained from the industrial sponsor, the data available from design drawings, schedules and manufacturers of specified products was not complete enough to meet requirements on data quality for chilled beam and DV systems. Specifically, a bill of materials or EPD could not be obtained for any terminal unit used in an active or passive chilled beam system, whilst no case studies were identified of DV systems that had been designed for office buildings.

As before, these shortcomings do not necessarily invalidate the findings discussed in chapter 5, that (a) differences in embodied carbon can exist between generic types of HVAC systems and between installed examples of one type of system; and (b) uncertainty analysis can indicate whether these differences are statistically significant. The first statement is a likely consequence of inherent differences in technologies and the types or quantities of components and raw materials found to be used by each HVAC system. The second statement refers to the known applicability of uncertainty propagation to comparison of LCA results (Heijungs and Lenzen, 2014). Therefore it can be argued that the ability of the method developed in chapter 5 to make meaningful comparisons between alternative HVAC systems is not constrained by the limitation of the scope of the case studies to three types of HVAC systems. Here again, further empirical research to expand the number and type of HVAC systems sampled would be important for the future development of the estimation method, as proposed in section 7.6.

8.6.5.3 Review of alternative methods

To what extent might alternative methods within the same overall research design have supported a more effective investigation of any of the research questions? This is discussed in relation to the choices of LCA methodology and the method of uncertainty analysis.

The most significant limitation of the choice of LCA methodology relates to the scope of the study. In meeting the research objectives around development and application of an estimation method for embodied carbon of building services (RO2 and RO3), the study focused mainly on the product stage of the building life cycle, or modules A1-A3 in the TC-350 standard (BSI, 2011). This meant that recurring and end of life embodied carbon impacts were excluded. This choice was made because calculation of both recurring and end of life embodied impacts of a building element depends on knowing the product stage impacts, on which data is scarce for building services systems (Passer et al, 2012). In this sense product stage impacts represent the main gap in knowledge. Calculation of EC for the product replacement stage (A4), requires multiplication of the value of EC for stages A1-A3 by the expected product service life. This has relevance to construction practitioners, because recurring EC impacts of building services systems from product replacement can be substantial (Birgisdottir et al, 2017). Another limitation was that operational carbon impacts were included in the component-level case study but not the study of HVAC systems and were treated deterministically rather than being included within the uncertainty analysis. Additional sources of uncertainty affecting both recurring embodied and operational carbon emissions would include uncertainty about the time value of emissions, a factor that was excluded from the limited examinations of operational and recurring emissions in sections 5.4.5.3 and 8.3.1.2 of this study. Both of these limitations in scope represented trade-offs against the need to maximise project time and resources focused on investigation of product stage impacts of building services. Equally, both topics could represent avenues for further research.

The second research objective (RO2) also required uncertainty analysis to be incorporated into the estimation of embodied carbon. To do so entailed two methodological choices. The first was to focus on parameter uncertainty rather than model or scenario uncertainty and the second was to compare two specific methods of uncertainty propagation, Monte Carlo simulation (MCS) and first order analytical propagation (AUP). Would alternative choices in either case have enabled a more robust or thorough approach to be used to meet the objective? In the first case, the focus on parameter uncertainty was necessary to capture the uncertainty around the values for mass, material type and product stage EC coefficients for composite build services components. Had the scope of the analysis included recurring EC impacts, uncertainty propagation could have measured the effects of scenario uncertainty associated with product condition and replacement cycles on nominal service lives of individual components. This could be an area for further research. Concerning model uncertainty, its impact was much reduced by adhering to relevant ISO standards (BSI, 2011, 2014) and focusing on the environmental impact indicator used by other EC studies, GWP 100. This was necessary as the objective was to develop an estimation method that was reliable in that it could be applied to other case studies without requiring a bespoke LCA study in each case.

The choice of uncertainty propagation methods was made because MCS is a widely used sampling method and AUP has been found to be computationally more efficient than a range of alternatives, including MCS, Latin Hypercube simulation (LHCS) and fuzzy interval analysis (FIA) (Groen et al, 2014). However, the AUP method could have been extended to the second order of the Taylor series, which would have enabled the effects of non-linear errors in the probability distributions of input parameters to be represented (Mekid and Vaja, 2008, Pfingsten et al, 2017). Such a method could offer greater convergence between the results of AUP and those of MCS. A practical counter argument against using the second order method is that differences measured between results of propagation using first order AUP and those obtained using of MCS are only substantial if the uncertainties are relatively large. Differences between results obtained by each method were found of 3.7% for uncertainties with a coefficient of variation (CV) of 20%, rising to a difference of 8% for uncertainties with a CV of 35% (Pfingsten et al, 2017). It could be argued that uncertainties of this magnitude, regardless of the propagation method used, are equally unacceptable for design practitioners wishing to compare embodied carbon between HVAC systems (Heijungs, 2016). With either of the AUP methods, identification of significant differences between embodied carbon impacts of alternative HVAC options would be challenging if at all possible. Application of the iterative method to combine uncertainty analysis and uncertainty reduction as discussed in chapter 8 would in such cases provide a strategy for improving the ability of embodied carbon estimates to support a meaningful choice between HVAC options.

8.6.6 Chapter summary

This study aimed to improve understanding of embodied environmental impacts of building services systems in commercial office buildings. At a practical level the problem space was characterised as involving a lack of suitable data, methods and tools for the estimation of those impacts. Conceptually, the problem was investigated by focusing on two distinct types of uncertainty, one relating to input parameters and the other relating to decision-making by design practitioners. The results of the study provide a method in which gaps in data on building services systems, particularly regarding raw material content, can be addressed by a parametric estimation method. The method develops a set of default input parameter values for the masses and embodied carbon coefficients and of generic types of HVAC components and systems, based on empirical case studies. First-order analytical uncertainty propagation (AUP) is then used to calculate the effect of uncertainty of these input parameters on the estimated value of embodied carbon for the HVAC component or system. The use of AUP is shown to provide a computationally efficient alternative to Monte Carlo sampling (MCS), against which is tested and found able to produce results that are not significantly different. The method is open to continuous improvement as more empirical data becomes available, as this data is integrated into the method by an iterative combination of uncertainty analysis and uncertainty reduction. The method is relevant to practitioners in that it supports decision-making to reduce embodied carbon in HVAC systems during the early stages of building design. Implementation of the method is supported by the inclusion of a functional specification for a software tool aligned to the RIBA Plan of Work (RIBA, 2013).

Valuable insights into how practitioners make decisions that can influence embodied carbon impacts of HVAC systems were identified by qualitative study of mechanical services engineers. This complemented the findings of an initial construction industry survey that mapped various barriers to embodied carbon reduction along with the most suitable intervention measures to address these barriers. The qualitative study highlighted the potential scope of influence of mechanical services designers on decisions that may reduce embodied carbon, whilst showing that these benefits are not always recognised if achieved as a result of materially efficient design practice or a strategy to promote natural or mixed mode ventilation. The use of theories of rational choice and bounded rationality as a lens through which to explain decision-making by practitioners helped inform strategies for improving decision support for embodied carbon reduction tailored to the needs of practitioners. These included 'reframing' of interventions to align with existing good practice, better communication of EC reduction strategies and available policy incentives and the provision of practical estimation tools as outlined in chapter 7.

8.7 Recommendations

The findings of this study identify a number of areas in which further research or action would be beneficial. These are divided into (a) recommendations for further research to extend the work of chapters 5 and 7 of this study; and (b) wider recommendations directed towards the embodied carbon research community, construction industry practitioners and policy-makers.

8.7.1 Further research

(a) *Further development of the embodied carbon estimation method by expanding the scope of building services components and systems covered.*

As outlined in section 7.6, this would also contribute to the forward strategy for developing content of an electronic EC estimation tool. It is recommended that an expansion in the sample size and range of generic types of HVAC components should be followed by an expansion in the range of building services disciplines to cover electrical and public health services. The use of an iterative approach to combine uncertainty reduction and uncertainty analysis as outlined in section 8.3.1.5 would then enable the development of increasingly robust default values for nominal embodied carbon and input uncertainty of raw material mass.

(b) *Further development of the embodied carbon estimation method by expanding the scope of life cycle stages covered.*

In principle, the estimation method could be expanded to include embodied carbon emissions for recurring and end of life stages of HVAC component and system life, as discussed in section 8.6.5.3. A previous study has applied AUP to product stage and recurring embodied carbon of a residential case study (Hoxha et al, 2014). As this did not consider building services systems of the scale or complexity found in office buildings, or end of life impacts, it is recommended that further work in this area should be developed. As a further step, the estimation method of this study could potentially be integrated with estimation of operational carbon emissions, building on the example used in section 5.4.5.3, but with uncertainty analysis applied to operational as well as embodied carbon. Conceptually, integration would make more sense at the level of an HVAC system rather than an individual component. This is because not all parts of the system consume any energy associated with operational emissions, but the system as a whole has a profile associated with its total operational emissions in meeting thermal demands over a given period.

(c) *Further development of the specification for the estimation tool into a working model.*

As the purpose of the specification in chapter 7 is to inform the development of a software-based solution, it is recommended that further work to prototype, test, analyse and refine the solution should take place. As indicated in section 7.6, this could initially be implemented using off-the-shelf software such as Microsoft Excel, which was the platform used to develop the underlying estimation method.

8.7.2 Recommendations for the research community, industry and policy-makers

(d) *Definitions of embodied and whole-life carbon.*

In the interests of clarity and harmonisation, it is recommended that the term 'whole-life carbon' should refer to carbon emissions during all of the modules from A1 to C4 of the TC 350 standards (BSI, 2011, 2014). This will ensure that the 'benefits and loads beyond the system boundary' of reuse, recovery and recycling potential after the end of life of a building in stage D (BSI, 2011, 2014) are only counted in relation to any additional built assets to which they contribute. The term 'embodied carbon' should be defined as widely as possible to cover this definition of whole-life carbon minus the stages for use (B1), operational energy use (B6) and operational water use (B7). Embodied carbon will thus describe the product stage of raw material supply, transport and manufacturing (A1-A3), the use stages of maintenance, repair, replacement and refurbishment (B2-B5) and the end of life stages of deconstruction/demolition, transport, waste processing and disposal (C1-

C4). Where an estimation or mitigation measure is targeted at a subset of these stages, such as product stage embodied carbon, its scope should be described by the relevant ISO modules, as has been done within this study.

(e) *Extension of building regulations to cover whole-life carbon.*

The findings of chapters 4 and 6 make it clear that building regulations are considered by UK construction stakeholders to be one of the most effective incentives to promote behaviour change in the industry. It is therefore fitting to support the existing recommendation to government of a UK construction industry-led taskforce that 'the Building Regulations should be developed to eventually include whole-life carbon emissions' (Embodied Carbon Industry Taskforce, 2014) and to recommend further that whole-life carbon should be considered by the forthcoming government consultation on Part 'L' of the UK Building Regulations (BEIS, 2019).

(f) *Inclusion of building services in embodied carbon estimation standards.*

The latest RICS standard on whole-life carbon assessment in buildings lacks clarity on whether building services systems should be included in scope, especially for the product stage (RICS, 2017) and this lack of clarity affects the UKGBC definition of net zero carbon (UKGBC, 2019), as was discussed in section 2.5.1. This presents an anomaly for practitioners, given that the assessment of product-stage life cycle impacts of 'core building services' can now earn an exemplary BREEAM credit (BRE, 2018). It is therefore recommended that the RICS standard be updated to include building services systems within the minimum assessment requirements for all life cycle stages within the scope of a whole-life carbon assessment of a built asset.

(g) *Environmental product declarations.*

There are major challenges around the use of environmental product declarations (EPDs) compliant with ISO 15804 as data sources for life cycle impacts of building services components. These include the relative scarcity of EPDs on products of this type and the lack of a consolidated reference website on which all nationally produced EPDs can be found, both of which were discussed in section 2.5.4. A further challenge is the lack of knowledge about EPDs found among construction practitioners, which was discussed in section 4.5.2. While this study argues that parametric embodied carbon estimation methods can offer an alternative to the use of EPDs where none have been produced, it is also appropriate to recommend that industry bodies such as BRE and CIBSE should promote better communication about the availability and benefits of existing EPDs, especially those covering building services. It is further recommended that an agreement should be made between EPD International and the various national associations such as IBU on a method to make all published EPDs that are compliant with ISO 15804 easily accessible to practitioners in a single location.

(h) *Decision support for construction practitioners.*

The findings of chapters 4 and 6 indicate that in addition to 'hard' policy incentives such as building regulations and technical support in the form of better estimation methods and tools, there is a need for greater communication and understanding about existing strategies of embodied carbon reduction, particularly where interventions can be 'framed' to align with recognised work practices. The publication that inspired this research (CIBSE 2014a) identifies a range of practical strategies for increasing resource efficiency and reducing embodied carbon in building services design as well as identifying how these interventions align with recognised work practices on cost efficiency and lean design. However the findings of chapters 4 and 6 of this study indicate that many building services designers and clients are not familiar with these strategies. It is therefore recommended that more is done by CIBSE and other industry bodies to disseminate the contents of that publication to practitioners (CIBSE, 2014a).

(i) *More life cycle inventory data on building services components.*

The most effective means to improve embodied carbon estimation on building services systems would be for more data on bills of materials and energy consumed in supply chains of products to be made available by manufacturers. However as discussed in section 8.6.5.2, some manufacturers are unwilling to release data because of fears about confidentiality or the lack of a perceived commercial advantage in doing so. Equally, the business case (in terms of reputational benefits) for obtaining a third-party certified EPD may be outweighed by the cost of commissioning the EPD, which must be borne by the manufacturer. However, if UK building regulations were extended to cover embodied carbon, any manufacturer of building products unable to provide LCI data might immediately be at a disadvantage, whether or not EPDs or a cheaper alternative were required to show compliance. It is therefore recommended that manufacturers of building services products who are interested in future-proofing work more closely with the embodied carbon research community on cost-effective ways to provide LCI data for generic classes of building services products.

9 References

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Appendix 1: RIBA Plan of Work (RIBA, 2013)

RIBA

The RIBA Plan of Work 2013 organises the process of briefing, designing, constructing, maintaining, operating and using building projects into a number of key stages. The content of stages may vary or overlap to suit specific project requirements. The RIBA Plan of Work 2013 should be used solely as guidance for the preparation of detailed professional services contracts and building contracts.

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RIBA Plan of Work 2013 — Stages / Tasks	0 Strategic Definition	1 Preparation and Brief	2 Concept Design	3 Developed Design	4 Technical Design	5 Construction	6 Handover and Close Out	7 In Use
Core Objectives	Identify client's **Business Case** and **Strategic Brief** and other core project requirements.	Develop **Project Objectives**, including **Quality Objectives** and **Project Outcomes**, **Sustainability Aspirations**, **Project Budget**, other parameters or constraints and develop **Initial Project Brief**. Undertake **Feasibility Studies** and review of **Site Information**.	Prepare **Concept Design**, including outline proposals for structural design, building services systems, outline specifications and preliminary **Cost Information** along with relevant **Project Strategies** in accordance with **Design Programme**. Agree alterations to brief and issue **Final Project Brief**.	Prepare **Developed Design**, including coordinated and updated proposals for structural design, building services systems, outline specifications, **Cost Information** and **Project Strategies** in accordance with **Design Programme**.	Prepare **Technical Design** in accordance with **Design Responsibility Matrix** and **Project Strategies** to include all architectural, structural and building services information, specialist subcontractor design and specifications, in accordance with **Design Programme**.	Offsite manufacturing and onsite **Construction** in accordance with **Construction Programme** and resolution of **Design Queries** from site as they arise.	Handover of building and conclusion of **Building Contract**.	Undertake **In Use** services in accordance with **Schedule of Services**.
Procurement *Variable task bar	Initial considerations for assembling the project team.	Prepare **Project Roles Table** and **Contractual Tree** and continue assembling the project team.	<---- The procurement strategy does not fundamentally alter the progression of the design or the level of detail prepared at a given stage. However, **Information Exchanges** will vary depending on the selected procurement route and **Building Contract**. A bespoke **RIBA Plan of Work 2013** will set out the specific tendering and procurement activities that will occur at each stage in relation to the chosen procurement route. ---->			Administration of **Building Contract**, including regular site inspections and review of progress.	Conclude administration of **Building Contract**.	
Programme *Variable task bar	Establish **Project Programme**.	Review **Project Programme**.	Review **Project Programme**.	<-- The procurement route may dictate the **Project Programme** and may result in certain stages overlapping or being undertaken concurrently. A bespoke **RIBA Plan of Work 2013** will clarify the stage overlaps. The **Project Programme** will set out the specific stage dates and detailed programme durations. -->				
(Town) Planning *Variable task bar	Pre-application discussions.	Pre-application discussions.	<------ Planning applications are typically made using the Stage 3 output. A bespoke **RIBA Plan of Work 2013** will identify when the planning application is to be made. ------>					
Suggested Key Support Tasks	Review **Feedback** from previous projects.	Prepare **Handover Strategy** and **Risk Assessments**. Agree **Schedule of Services**, **Design Responsibility Matrix** and **Information Exchanges** and prepare **Project Execution Plan** including **Technology** and **Communication Strategies** and consideration of **Common Standards** to be used.	Prepare **Sustainability Strategy**, **Maintenance and Operational Strategy** and review **Handover Strategy** and **Risk Assessments**. Undertake third party consultations as required and any **Research and Development** aspects. Review and update **Project Execution Plan**. Consider **Construction Strategy**, including offsite fabrication, and develop **Health and Safety Strategy**.	Review and update **Sustainability**, **Maintenance and Operational** and **Handover Strategies** and **Risk Assessments**. Undertake third party consultations as required and conclude **Research and Development** aspects. Review and update **Project Execution Plan**, including **Change Control Procedures**. Review and update **Construction** and **Health and Safety Strategies**.	Review and update **Sustainability**, **Maintenance and Operational** and **Handover Strategies** and **Risk Assessments**. Prepare and submit Building Regulations submission and any other third party submissions requiring consent. Review and update **Project Execution Plan**. Review **Construction Strategy**, including sequencing, and update **Health and Safety Strategy**.	Review and update **Sustainability Strategy** and implement **Handover Strategy**, including agreement of information required for commissioning, training, handover, asset management, future monitoring and maintenance and ongoing compilation of **'As-constructed' Information**. Update **Construction** and **Health and Safety Strategies**.	Carry out activities listed in **Handover Strategy** including **Feedback** for use during the future life of the building or on future projects. Updating of **Project Information** as required.	Conclude activities listed in **Handover Strategy** including **Post-occupancy Evaluation**, review of **Project Performance**, **Project Outcomes** and **Research and Development** aspects. Updating of **Project Information**, as required, in response to ongoing client **Feedback** until the end of the building's life.
Sustainability Checkpoints	**Sustainability Checkpoint — 0**	**Sustainability Checkpoint — 1**	**Sustainability Checkpoint — 2**	**Sustainability Checkpoint — 3**	**Sustainability Checkpoint — 4**	**Sustainability Checkpoint — 5**	**Sustainability Checkpoint — 6**	**Sustainability Checkpoint — 7**
Information Exchanges (at stage completion)	**Strategic Brief.**	**Initial Project Brief.**	**Concept Design** including outline structural and building services design, associated **Project Strategies**, preliminary **Cost Information** and **Final Project Brief**.	**Developed Design**, including the coordinated architectural, structural and building services design and updated **Cost Information**.	Completed **Technical Design** of the project.	**'As-constructed' Information.**	Updated **'As-constructed' Information.**	**'As-constructed' Information** updated in response to ongoing client **Feedback** and maintenance or operational developments.
UK Government Information Exchanges	Not required.	Required.	Required.	Required.	Not required.	Not required.	Required.	As required.

***Variable task bar** – in creating a bespoke project or practice specific RIBA Plan of Work 2013 via www.ribaplanofwork.com a specific bar is selected from a number of options.

Appendix 2: Scoping interviews

A series of semi-structured, scoping interviews were held with building services engineers, other construction stakeholders and academic researchers in order to identify challenges and opportunities associated with resource efficiency of building services systems for non-domestic buildings in the UK. The scoping interviews and the literature review in chapter 2 were used to inform the research objectives outlined in chapter 1. Topics covered included (a) the source and timing of decisions during a construction project about resource efficiency of building services systems; (b) stakeholder groups involved in such decisions; (c) how decisions are implemented on choice of materials, service design, re-use and recycling; (d) types of data and tools that might support such decisions; and (e) perceived barriers to, and opportunities for, greater environmental resource efficiency in building services systems.

The profile of interviewees is summarised in Table A.1.

Table A.1: Profile of interview participants for scoping interviews

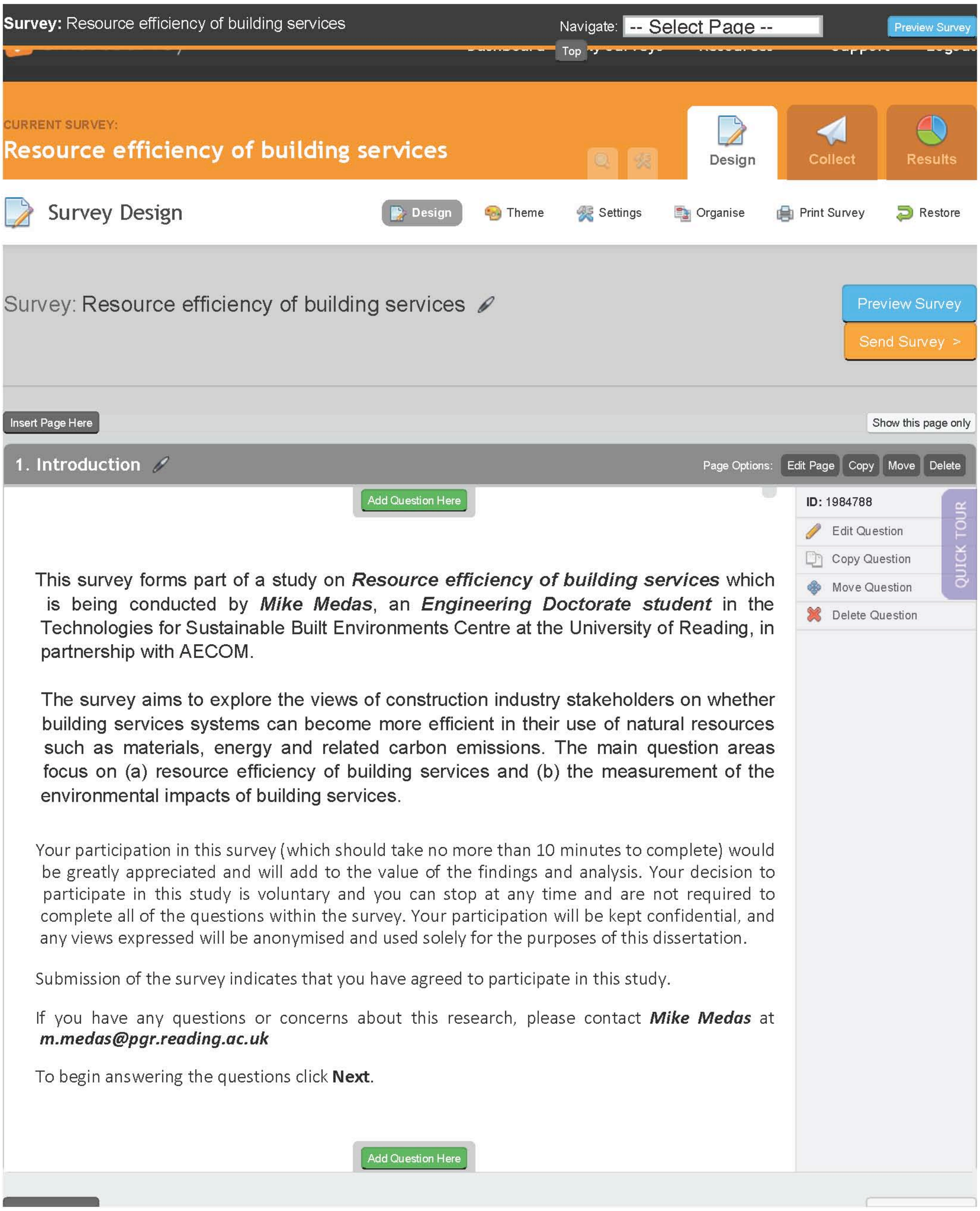
Interviewee	Job role	Areas of expertise	Years of experience
A	Consultant	Cost consultancy/embodied carbon analysis	30+
B	Academic researcher	Structural engineering/embodied carbon analysis	30+
C	Regional director	Building services engineering	26
D	Regional director	Building services engineering	25
E	Director	Cost consultancy	17
F	Business development manager	Manufacturing of building services components	14
G	Associate Director	Building services engineering	14
H	Regional director	Building information modelling	12
I	Head of sustainability	Sustainability and embodied carbon from construction client perspective	10
J	Sustainability manager	Sustainability and embodied carbon from construction client perspective	10
K	Academic researcher	Structural engineering/embodied carbon analysis	7
L	Academic researcher	Production engineering/embodied carbon analysis	6

Table A.2: Findings of scoping interviews on resource efficiency of building services

Topic	Summary of responses
Source and timing of decisions on resource efficiency of building services systems	Client priorities are key, as is cost and rules of thumb in system design and choice of components. Contract specification of building services also relevant. Key decisions start early during the design stages, i.e. during concept design or earlier.
Stakeholders involved in decisions	Decisions are usually collaborative, with key roles for client, building services engineer and main contractor. Also designer for base build and fit-out, subcontractors for mechanical and electrical (M&E) service installation and supply, demolition and disposal. For re-use market, engineers and remanufacturers.
How decisions are implemented	Depends on project brief, priorities of stakeholders, awareness of resource efficiency options, level of integration between stakeholders.
Data and tools to support decisions	Some demand from clients to measure embodied impacts of building services, but limited data. Inclusion of embodied values in standard building services contract specification would help resource efficient option choice. Decision making tools must be simple to use at design stage and measure building services impacts including their interactions with building fabric.
Barriers & opportunities - reducing material consumption	Barriers: No big driver unless clients requests it. Risk of specification being too prescriptive, autonomy of contractor to select equipment. Plausible reasons exist to oversize or over-specify equipment. Sizing of equipment led by energy consumption rather than embodied content. Opportunities: If cost efficiency and performance can be maintained, lower mass or lower-impact substitute materials can be viable.
Barriers & opportunities - reducing wastage	Barriers: Some inconsistency in definitions of waste, lack of information on destination of building services waste. Opportunity: Data for embodied impacts can include a wider definition of waste, waste tracking can be trialed
Barriers & opportunities - increase reuse/ recycled content	Barriers: Quality concerns exist about used building services equipment, some parts not standardised. Opportunities: Some manufacturers already design for disassembly.
Barriers & opportunities - products with low embodied carbon and water	Barriers: Lack of data, substitution may be challenged by perceived quality of materials, product choice led by performance, need to mitigate risk and fact that engineer cannot specify kit in too much detail. Opportunities: Once data is available, client requirements often not prescriptive in specifying M&E kit, so scope for innovation exists. In reviewing projects, data can be compiled from LCA databases or calculated from bills of quantities, equipment suppliers and/or original drawings.

Appendix 3: Survey questionnaire

Survey Design - SmartSurvey Control Panel



This survey forms part of a study on ***Resource efficiency of building services*** which is being conducted by ***Mike Medas***, an ***Engineering Doctorate student*** in the Technologies for Sustainable Built Environments Centre at the University of Reading, in partnership with AECOM.

The survey aims to explore the views of construction industry stakeholders on whether building services systems can become more efficient in their use of natural resources such as materials, energy and related carbon emissions. The main question areas focus on (a) resource efficiency of building services and (b) the measurement of the environmental impacts of building services.

Your participation in this survey (which should take no more than 10 minutes to complete) would be greatly appreciated and will add to the value of the findings and analysis. Your decision to participate in this study is voluntary and you can stop at any time and are not required to complete all of the questions within the survey. Your participation will be kept confidential, and any views expressed will be anonymised and used solely for the purposes of this dissertation.

Submission of the survey indicates that you have agreed to participate in this study.

If you have any questions or concerns about this research, please contact ***Mike Medas*** at ***m.medas@pgr.reading.ac.uk***

To begin answering the questions click **Next**.

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2. Information about your role

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* 1. Your role

Name of your company / organisation

Job title

Years of experience

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* 2. Which of the following categories describe your main area of work? (Please tick ALL that apply)

- ☐ Design of building services
- ☐ Specification of building services
- ☐ Commissioning of building services
- ☐ Installation of building services
- ☐ Operation and maintenance of building services
- ☐ Manufacturer of building services systems or components
- ☐ Supplier of building services systems or components
- ☐ Demolition / strip out contractor
- ☐ Disposal contractor
- ☐ Research
- ☐ Other (please specify):

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3. Resource efficiency of building services - general

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* 3. Do you believe that building services systems and components should be designed to be more efficient in their use of natural resources such as materials, energy and water?

- ○ Yes
- ○ No
- ○ Don't know / Other

Please provide a brief explanation of your answer

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4. Resource efficiency of building services - general

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* 4. Please indicate the extent to which you consider that the following activities can be effective in making building services more efficient in their use of natural resources; from 'Very Ineffective' to 'Very Effective'.

	Very Ineffective	Quite Ineffective	Neither Effective nor Ineffective	Quite Effective	Very Effective	Don't Know
Increasing the reused and recycled content of building services	○	○	○	○	○	○
Matching the durability and lifespan of building service assets to their service life	○	○	○	○	○	○
Using resources in manufacturing with no scarcity and security issues	○	○	○	○	○	○
Using products with lower embodied carbon and embodied water	○	○	○	○	○	○
Reducing energy use during manufacturing or construction	○	○	○	○	○	○
Reducing waste in manufacturing, operation and at end of life	○	○	○	○	○	○
Enabling energy efficiency and water efficiency during the operational life of building services	○	○	○	○	○	○
Minimising the cost of manufacturing or installing building services	○	○	○	○	○	○
Using BIM (building information modelling) to design building services more efficiently	○	○	○	○	○	○

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5. Resource efficiency of building services - general

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* 5. In your opinion, which three of the following groups of stakeholders have the most influence in making building services systems and components more efficient in their use of natural resources?

- ☐ Construction clients
- ☐ Building services engineers in the design team
- ☐ Other members of the building design team
- ☐ Building services contractors
- ☐ Facilities managers
- ☐ Building users
- ☐ Manufacturers of building services systems / components
- ☐ Government / policy makers

Please comment to add other stakeholders not listed above or to explain your answer

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* 6. In your opinion, how important are the following activities in influencing whether building services systems and components are efficient in their use of natural resources, from ''Very Unimportant' to 'Very important? ?

	Very Unimportant	Quite Unimportant	Neither Important nor Unimportant	Quite Important	Very Important
Early design decisions on building form and level of building servicing	○	○	○	○	○
The choice of system type – e.g. centralised or decentralised HVAC, fan coil units or chilled beams, etc.	○	○	○	○	○
The drafting of the project's MEP design specification	○	○	○	○	○
The choice of individual products to meet a given MEP design specification	○	○	○	○	○

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6. Resource efficiency of building services - general

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* 7. In your opinion, how important are the following issues when specifying particular choices of building services systems or components in a construction project, from 'Very Unimportant' to 'Very Important?'

	Very Unimportant	Quite Unimportant	Neither important nor unimportant	Quite Important	Very Important
Performance	○	○	○	○	○
Reliability	○	○	○	○	○
Durability / lifespan	○	○	○	○	○
Operational energy consumption	○	○	○	○	○
Level of embodied energy or embodied carbon	○	○	○	○	○
Scarcity of materials used in manufacturing	○	○	○	○	○
Level of recycled content	○	○	○	○	○
Ease of dismantling / deconstruction	○	○	○	○	○
Potential for re-use at end of life	○	○	○	○	○
Length of maintenance / refurbishment cycle	○	○	○	○	○

Economic cost	○	○	○	○	○

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7. Resource efficiency of building services - general

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* 8. In your opinion, how important are the following priorities in a typical construction project, from ''Very Important' to 'Very Unimportant?

	Very Important	Quite important	Neither important nor un-important	Quite Unimportant	Very Unimportant
Energy use and carbon emissions incurred during the operational life of the building	○	○	○	○	○
Energy use & carbon emissions from the manufacturing and construction of the building structure and envelope	○	○	○	○	○
Energy use & carbon emissions from the manufacturing and construction of the building services	○	○	○	○	○
Energy use & carbon emissions from the demolition or disposal of the building structure and envelope	○	○	○	○	○
Energy use & carbon emissions from the demolition or disposal of the building services	○	○	○	○	○

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8. Measuring the environmental impacts of building services

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* 9. Would you find it useful in your work if a software tool was available that enabled project designers to select building services systems and components and see the value of embodied carbon associated with a particular choice?

- ○ Yes
- ○ No
- ○ Don't know

Please provide a brief explanation of your answer

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9. Measuring the environmental impacts of building services

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* 10. Please indicate the extent to which you agree or disagree with the following statements, from 'Strongly Agree' to 'Strongly Disagree'

	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree	Don't know
In order to reduce carbon emissions, we need to measure embodied as well as operational carbon and energy impacts of buildings	○	○	○	○	○	○
Existing tools, methods and data sources are reliable for measuring embodied carbon of building services	○	○	○	○	○	○
Environmental Product Declarations (EPDs) are a reliable way to assess lifetime environmental impacts of building services	○	○	○	○	○	○
Full life cycle assessments (LCA) of products are a reliable way to assess lifetime environmental impacts of building services	○	○	○	○	○	○
Building Regulations can be helpful in persuading the construction industry to measure embodied carbon	○	○	○	○	○	○
Voluntary incentives can be helpful in persuading the construction industry to measure embodied carbon	○	○	○	○	○	○

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10. Measuring the environmental impacts of building services

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* 11. Please rate the extent to which you feel that the following factors might be effective or ineffective in developing greater knowledge in the construction industry about the embodied carbon impacts of building services systems and components, from "Very Effective' to 'Very Ineffective?

	Very Effective	Quite Effective	Nether Effective nor Ineffective	Quite Ineffective	Very Ineffective	Don't know
The current level of demand for the information from stakeholders	○	○	○	○	○	○
The current cost of obtaining the information	○	○	○	○	○	○
The suitability of currently available methods to measure embodied carbon	○	○	○	○	○	○
The suitability of currently available data on embodied carbon impacts	○	○	○	○	○	○
The suitability of existing suitable software tools	○	○	○	○	○	○
The role of existing Building Regulations	○	○	○	○	○	○
The role of existing voluntary incentives	○	○	○	○	○	○

If you feel there are other factors that might impact on this question, please give details below

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11. Feedback (Optional)

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12. Thank you for your participating in this questionnaire.

In order to help us gain greater insight into views of industry stakeholders, if you would be willing to be contacted for a brief telephone interview to discuss your opinion on these topics further, please provide your contact details below

Name

Email address

Contact telephone number

Add Question Here

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12. Thank You Page

You have completed this survey!

Thank you for taking the time to answer this survey!

Please go to the Survey Settings to modify thank you message and auto redirect settings.

Change Settings

Auto Redirect: ACTIVE **After:** 5 seconds **URL:** http://www.smartsurvey.co.uk/landing.aspx

Account Number: s56665

Appendix 4: Supplementary data on composite components

This section provides further details, in Table A4.1, of input parameters and data sources used for the composite components used in case studies of HVAC systems, of which a summary was given in Table 5.4.

Table A4.1: Further details of input parameters and data sources for composite components

Component and percentages of raw material(s)	Buildings in which used	Mass of component (kg)	Embodied carbon coefficient (ECC) (kg CO_2 e/kg mass)	Total embodied carbon (EC) (kg)	Source of data
Air-cooled chiller with centrifugal compressor, 2 No * 400kW cooling capacity	1				Mass, model type and cooling capacity obtained from contractor's schedule of installed equipment. Bill of materials (BOM) estimated based on Riviere et al, 2012b, p62. Embodied carbon coefficients (ECCs) from Hammond & Jones (H&J), 2011.
Galvanised steel - 80.16%		4537.06	1.54	6987.07	
Aluminium – 8.64%		489.02	9.16	4479.46	
Copper – 7.9%		447.14	2.71	1211.75	
PVC – 1.25%		70.75	3.1	219.33	
Polyethylene low density – 0.37%		20.94	2.08	43.56	
Brass – 0.32%		18.11	2.64	47.82	
Sub-total		5660	2.30	12,988.98	
Air-cooled chiller with centrifugal compressor, 1 No * 7760kW cooling capacity	4	32,428	2.30	74,683.46	BOM and ECCs as above. Cooling capacity estimated using notional cooling load for offices of 87 W/m^2 (BSRIA, 2011) * gross floor area * oversizing factor of 2. Total mass estimated proportionately to that of an EPD for a chiller of similar cooling capacity (Institut Bauen und Umwelt e.V., 2011).

Table A4.1 continued

Component and percentages of raw material(s)	Buildings in which used	Mass of component (kg)	ECC (kg CO_2 e/kg mass)	Total EC (kg)	Source of data
Air handling units, various sizes and specifications	1,2,3,4				
Galvanised steel – 60.9%		3481.98	1.54	5362.26	Mass from contractor's schedule of installed equipment. BOM estimated based on Heikkila, 2008, p56. ECCs from H&J, 2011. Values for mass and EC shown here are for all 3 AHUs in Building 1. Raw material percentages and ECCs were assumed identical for all air handling units (AHUs) in Buildings 1-4.
Steel, hot rolled – 18.3%		1032.37	1.46	1507.26	
Aluminium – 10.2%		459.86	9.16	4212.30	
Glass fibre – 9.1%		513.52	1.54	790.82	
Copper – 1.2%		66.9	2.71	181.54	
Plastics, various – 1.1%		63.61	3.31	210.56	
Stainless steel – 0.7%		37.14	6.15	228.39	
Sub-total		5655.47	2.21	12493.13	
Modular condenser boiler, 750 kW	1				
Cast iron – 64.1%		391.72	2.03	795.19	Mass from contractor's schedule of installed equipment in Building 1. BOM estimated based on Kemna et al, 2007, p7 and p12. ECCs from H&J, 2011.
Galvanised steel –31.25%		190.95	1.54	294.06	
Polypropylene plastic – 1.61%		9.85	3.96	39.00	
Rigid polyurethane – 1.29%		7.86	4.26	33.48	
Stainless steel - 0.78%		4.77	6.15	29.37	
Copper – 0.66%		4.01	2.71	10.87	
Polystyrene – 0.04%		0.23	3.43	0.80	
Sub-total		611.00	1.97	1202.76	

Table A4.1 continued

Component and percentages of raw material(s)	Buildings in which used	Mass of component (kg)	ECC (kg CO_2 e/kg mass)	Total EC (kg)	Source of data
Fan-assisted variable air volume (VAV) terminal units, various sizes.	4				Values for mass and raw materials shown here are from experimental tear-down analysis of terminal unit in Building 4, for which total mass exceeded that listed in manufacturer's product literature by 6.5%. Masses for other terminal units from contractor's schedule of installed equipment and manufacturer's product literature, with BOM assumed proportionate to that found by tear-down analysis. ECCs from H&J, 2011.
Galvanised steel – 82.73%		66.06	1.54	101.74	
General steel – 8.08 %		6.45	1.46	9.42	
Copper – 3.4%		2.71	2.71	7.35	
Various plastics– 2.24%		1.79	3.31	5.92	
Various electrical components - 2.05%		1.63	2.00	3.27	
Sub-total					
VRF indoor terminal units, various sizes and specifications	2,3				Raw materials estimated based on BOM for fan coil units of similar size due to similarity in technology. ECCs for raw material production, transport and manufacturing from H&J, 2011 and DEFRA/DECC, 2015 as listed in Table 5.3 of this study, assuming a similar manufacturing scrap rate of 30% for galvanised steel and 10% for PUR foam.
Galvanised steel – 74.47%					
Copper – 6.86%					
General steel – 6.47%					
Aluminium – 6.28%					
Polyurethane foam – 5.92%					
ECC for entire unit			2.75		
VRF rooftop condenser units, various sizes and specifications	2,3				Data sources as above
Galvanised steel – 66.87%					
General steel – 10.63%					
Aluminium – 8.58%					
Copper – 8.03%					
Polyurethane foam – 5.90%					
ECC for entire unit			2.90		

Appendix 5: Topic guide for qualitative study

This appendix includes a sample of an invitation letter for participants in qualitative interviews and the topic guide used as a basis for interviews. For question 2, participants were shown a diagram of air conditioning systems that is also reproduced in Figure 6.1 of this thesis.

Mike Medas
University of Reading
Technologies for
Sustainable Built Environments Centre
PO Box 220
Reading, Berks
RG6 6AF

m.medas@pgr.reading.ac.uk

(Insert name and address of participant)

(Insert date)

[Note – this letter will be used to follow a telephone request to participate in an interview]

Dear *(insert name of participant)*

Thanks for agreeing to participate in a telephone interview. As promised, here is a summary of my work and the format of the proposed interview. I am a research student working with AECOM and the University of Reading on a research project looking at 'Resource efficiency of building services', which aims to develop robust methods to measure the embodied life cycle impacts of typical building services systems and components. A pdf is attached summarising the research aims.

I am particularly interested in the views of MEP engineers/contractors/manufacturers on this area *(delete as applicable prior to completing letter*) and for this reason I would like to interview you as a key stakeholder from this sector.

The proposed telephone interview would be of about 40 minutes' duration at a time and date of your choice. The interview questions will be about your experience of resource efficiency of building services. You can choose not to answer any questions and you are free to withdraw from the study at any time. At every stage, your identity will remain confidential. Your name and all identifying information will be removed from the written transcript. My supervisor and I will be the only people who will have access to this data.

With your permission, I would like to tape the interview and transcribe it later. Copies of the transcript will be available on request and any changes which you ask for will be made. The data will be kept securely and destroyed when the study has ended, which will be a maximum of 12 months from the completion of the research. The data will be used for academic purposes only.

Copies of the completed dissertation will be available on request. If you have any further questions about the study, please feel free to contact me at the above address or by email.

This project has been subject to ethical review, according to the procedures specified by the University Research Ethics Committee, and has been given a favourable ethical opinion for conduct.

Please complete the electronic consent form **here** by return to confirm your agreement to be interviewed.

Yours sincerely

Mike Medas
Research Engineer
AECOM / University of Reading

HVAC/air conditioning - Topic guide for semi-structured interviews

Question topic *[With notes]*	**Theoretical relevance**
1. Personal details (not including name) / employer/ years of experience in industry / main area of work /how many office designs worked on	
2. Definition of systems	
• For a medium to large (over $1000m^2$) mechanically serviced office building in the UK designed within the last 10 years, what would you say are the five most common types of air-conditioning system used, based on the list in this diagram? Please any include systems, or combination of systems, not shown on the list. *(participants are then shown the HVAC system diagram attached below)* • In what order would you rank these systems, starting with the most common?	Verifying / amending the proposed shortlist of systems by presenting a wide selection of systems in the reference diagram (attached below)
3. Design decision-making - system choice In a medium to large office project, [either new build shell & core / Category A fit-out or refurbishment]:	

• Can you tell me about the decision to choose an air-conditioning system?
  • When and how is the decision made?
  • Who is involved in the decision and how much influence does each have?
  • What is the decision based on and what is your objective in that decision-making process?
	Identifying parties involved in choice, process, timing and determinants of choice and whether determinants are rational or otherwise

• Can you describe the information typically available to [the designer] about the suitability of these systems *[Exploring sources and whether adequate/equal information available about all systems]*	Whether 'perfect' choice of alternatives exists
• Is there ever a situation in which more than one system is able to meet the project brief equally well? If so what happens?	Whether choices are transitive
4. Design decision-making - sizing, layout and detailed specification Once one type of air conditioning system is chosen,	
• What factors influence the decisions on system (plant sizing and distribution layout? *[Exploring all factors including resource efficiency]*	Identifying whether rational or other criteria used and testing whether resource efficiency opportunities described in TM56 are understood/used
• When specifying components [e.g. terminal units, ducts, pipes] what informs the choice of raw materials? *[Exploring whether this includes materials with lower environmental impacts / reused components / components with recycled content]*	

5. Reducing embodied carbon	
• Using the information available on a typical office project do you think that it is possible for designers to reduce material use or embodied carbon in air conditioning systems and components – and if so, how? • On fit out or refurbishment jobs, what determines whether existing components are reused and how might reuse be increased?	Exploring scope for resource efficiency with present information levels and testing whether RE opportunities described in TM56 are understood/used
6. Proposed HVAC system selection guide/tool	

• If the value of embodied carbon of alternative air conditioning systems was available at early design stage:
  ◦ What form would it need to be presented in?
  ◦ What kind of information would be useful?
  ◦ Who would the audience be for the information?
  ◦ Would anything else be needed to encourage such a guide to be used?
	Informing development of the guide

7 If project files were accessible, what key data would you find it useful to be able to access from each project?	