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Assessing initial embodied energy in UK non-domestic construction projects

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ASSESSING INITIAL EMBODIED ENERGY IN UK NON-DOMESTIC CONSTRUCTION PROJECTS

By

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A dissertation thesis submitted in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD), at Loughborough University

October 2015

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ACKNOWLEDGEMENTS

This research project would not have been possible without the support, time and effort so many people kindly provided me throughout the years. Firstly, I wish to acknowledge the guidance received from my many academic and industry-based supervisors (Stephen Emmitt, Steven K. Firth, David Kerr, Russell Matthews, Dino Bouchlaghem, Rennie Chadwick, Kirk Shanks, and Andrew Nicholson) as without their dedication the completion of this research project would not have been possible.

Secondly, I wish to acknowledge the support and encouragement received from my closest friends and family, and in particular Sarah-Jane Holmes for truly being my inspiration. I am also grateful for all Centre for Innovative and Collaborative Engineering (CICE) staff members and my fellow EngD research engineers for making the past years an enjoyable experience.

Finally, I wish to acknowledge the research funding and support from the Engineering and Physical Sciences Research Council (EPSRC) and all VINCI Construction UK Limited staff who contributed to the findings of the research project. Their time and input during data capture was greatly appreciated.

Philip J. Davies

ABSTRACT

There is an increasing need to reduce energy consumption to tackle the adverse effects of climate change. The UK government has established numerous directives and policies to encourage carbon dioxide (CO_2) emission and energy reduction within the non-domestic sector. However these measures are primarily focused towards reducing operational energy (i.e. energy used during building occupier activity), largely overlooking initial embodied energy. The trend towards reduced operational energy consumption due to energy efficient design is leading initial embodied energy to become a more significant part of project life cycle energy. Initial embodied energy relates to the energy use during the material, transportation and construction phases up to project practical completion, which is of keen interest to contractors due to their significant role in project procurement and delivery.

Opportunities to address project life cycle energy are typically identified through a Life Cycle Assessment (LCA). However at present there is little validated data, no coherent method for data capture and limited incentive for project stakeholders to address initial embodied energy consumption. In response, this research project presents a contractor's practical approach towards assessing initial embodied energy consumption within UK non-domestic construction projects. An action research methodological approach enabled the assessment and potential reduction of initial embodied energy to be explored within a large principal contractor through five research cycles which included diagnosing and action planning, action taking, evaluating and specified learning.

A comprehensive framework is designed to highlight the significance of initial embodied energy consumption relative to specific construction packages, activities and sub-contractors. This framework is then explored within three UK non-domestic construction projects (i.e. two

industrial warehouses and one commercial office). Capturing information from live projects enables practical challenges and opportunities inherent when addressing initial embodied energy consumption to be identified. A series of contractor current practices are reviewed, and subsequently improved, to enhance their compliance with the framework requirements.

The findings emphasise the importance of material phase impacts, especially construction packages which primarily contain steel and concrete-based materials (i.e. ground and upper floor, external slab and frame). The importance of project type, site area, building lifespan and waste consumption are also recognised to reduce initial embodied energy consumption. The framework provides a practical approach for initial embodied energy assessment which can readily be adopted to help highlight further opportunities to reduce energy consumption. The research project concludes by presenting a number of recommendations for consideration by the construction industry and associated stakeholders, along with requirements for future research.

KEY WORDS

Initial embodied energy, contractor, non-domestic, material, transportation, construction, framework.

ACRONYMS AND ABBREVIATIONS

AP	‘All Projects’ model
BIM	Building Information Modelling
BoQ	Bill of Quantities
BREEAM	Building Research Establishment Environmental Assessment Method
CCA	Climate Change Agreement
CDP	Carbon Disclosure Project
CEEQUAL	Civil Engineering Environmental Quality Assessment and Award Scheme
CEN TC 350	European Committee for Standardization Technical Committee
CICE	Centre for Innovative and Collaborative Engineering
CO_2	Carbon dioxide
COINS	Construction industry solutions
CON	Construction life cycle phase
CRC	Carbon Reduction Commitment Energy Efficiency Scheme
CS	Case Study
CSR	Corporate Social Responsibility
DECs	Display Energy Certificates
DL	Director Level
E&S	Environmental and Sustainability Team
EE	Embodied energy
EMS	Environmental Management System
EngD	Engineering Doctorate
EPCs	Energy Performance Certificates
EPDs	Environmental Performance Declarations

EPI	Environmental Performance Indicator Procedure
EPSRC	Engineering and Physical Sciences Research Council
EU	European Union
FSC	Forest Stewardship Council
GHG	Greenhouse gas
GJ	Gigajoule
HVAC	Heating, Ventilation and Air Conditioning
Hy	Hybrid-based method
ICE	Inventory of Carbon and Energy
I-O	Input-output-based method
ISO	International Organization for Standardization
$kgCO_2e$	Kilogram of carbon dioxide equivalent
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LC-ZEB	Low Carbon-Zero Energy Building
MAT	Material life cycle phase
$MtCO_2$	Megatonne of carbon dioxide
NRI	Nominated Responsible Individual
OL	Operative Level
OP	Operational energy
OPP	Operative
P&E	Plant and equipment
PEFC	Programme for the Endorsement of Forest Certification
PL	Project Level
PLE	Project life cycle energy

PoW	Programme of Works
PQQ	Project Qualification Questionnaire
Pro	Process-based method
PT	'Project Type' model
PUWER	Provision and Use of Work Equipment Regulations
R&I	Retail and Interiors Division
RE	Research Engineer
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model
SPSS	Statistical Package for Social Science
SWMP	Site Waste Management Plan
TRAN	Transportation life cycle phase
UK	United Kingdom
VINCI	VINCI Construction UK Limited

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LIST OF PUBLICATIONS

The following publications have been produced during the research in partial fulfilment of the requirements for the award of the degree Doctor of Engineering (EngD). Four research papers were published and are included in the appendices of this thesis.

PAPER 1 (SEE APPENDIX A)

Davies, P.J., Emmitt, S., Firth, S.K. (2013a) On-site energy management challenges and opportunities: a contractor's perspective. *Building Research & Information*, 41(4), 450-468.

PAPER 2 (SEE APPENDIX B)

Davies, P.J., Emmitt, S., Firth, S.K., Kerr, D. (2013b) Addressing embodied energy from a contractor's perspective. *Sustainable Building Conference SB13*, 3-5 July, Coventry.

PAPER 3 (SEE APPENDIX C)

Davies, P.J., Emmitt, S., Firth, S.K. (2014) Challenges for capturing and assessing initial embodied energy: a contractor's perspective. *Construction Management and Economics*, 32(3), 290-308.

PAPER 4 (SEE APPENDIX D)

Davies, P.J., Emmitt, S., Firth, S.K. (2015) Delivering improved initial embodied energy efficiency during construction. *Sustainable Cities and Society*, 14, 267-279.

INDUSTRY ARTICLE

Davies, P. J. (2013) Assessing embodied energy during construction. *Innovation & Research Focus*, 92, 3. Available at: http://goo.gl/i94el6 (accessed on 11.12.14).

1 RESEARCH INTRODUCTION

This chapter provides an introduction to the Engineering Doctorate (EngD) thesis and the overall subject of initial embodied energy. The context and need for the research project from the perspective of the industrial sponsor and the wider UK construction industry, including the aim and objectives of the research, are defined.

1.1 Background to the Research

The effects of climate change need to be tackled through mitigation (IPCC, 2014). The worldwide construction industry is a major contributor towards climate change and is responsible for significant energy consumption (Zimmermann et al., 2005; Asif et al., 2007; UNSBCI, 2009; Rai et al., 2011). There is an increasing need to reduce energy consumption to address the adverse effects of climate change. The UK government has established numerous directives and policies to encourage energy and subsequent CO_2 emissions within the non-domestic sector; however these measures are primarily focused towards addressing operational energy, largely overlooking initial embodied energy (BIS, 2010; Hernandez and Kenny, 2010).

Project life cycle energy is derived from operational and embodied energy. Operational energy relates to the energy use during building occupier activity (such as heating, cooling, lighting) whereas embodied energy relates to the indirect and direct energy inputs required for various forms of construction (including renovation, maintenance, refurbishment, modification, and demolition) (Cole 1999; Dixit et al., 2010; Davies et al., 2013b; Davies et al., 2014). Typically embodied energy represents the smallest proportion of project life cycle energy (Gustavsson et al., 2010), although as operational energy diminishes due to improved energy efficient design, embodied energy will become a more significant part of project life cycle energy (Fieldson and Rai, 2009; Janssen, 2014). Thus addressing embodied energy through improved assessment can help identify opportunities to decrease total project life cycle energy and subsequent CO_2 emissions (Huberman and Pearlmutter, 2008; DECC, 2009a; Kneifel, 2010; RICS, 2010). In particular, initial embodied energy relates to the energy use during the material, transportation and construction phases up to project practical completion, which is of keen interest to contractors due to their significant role in project procurement and delivery (Goggins et al., 2010; Li et al., 2010; Monahan and Powell, 2011; Davies et al., 2013a; Davies et al., 2013b; Wong et al., 2013).

Opportunities to address the life cycle environmental impacts of products, processes or projects are typically identified through a Life Cycle Assessment (LCA) or Life Cycle Energy Assessment (LCEA) when energy is the primary environmental indicator. Seemingly the availability and accuracy of life cycle energy data is dependent upon many various project factors and decisions made by practitioners, which limits consistency in results (Treloar et al., 2000; Optis and Wild, 2010; Dixit et al., 2012; Cabeza et al., 2013; Ding and Forsythe, 2013). Hence, there is a need for robust life cycle energy data within the UK non-domestic sector to help project stakeholder’s understand the value of reduced energy consumption and to ensure buildings are constructed and operated as intended (LCICG, 2012). However, at present there is no coherent practical approach and limited incentive for project stakeholders to address initial embodied energy consumption (Sodagar and Fieldson, 2008; Hamilton-MacLaren et al., 2009; BIS, 2010; Ko, 2010; Monahan and Powell, 2011; Dixit et al., 2012; Davies et al., 2013a; Davies et al., 2013b; Giesekam et al., 2014).

1.2 Research Context

The requirement for this research originated in 2010 from a need recognised by VINCI Construction UK Limited to improve their awareness and application of a life cycle approach within construction projects. The need coincided with changes in the organisation's company strategy to reflect the contemporary agendas of key clients such as Tesco PLC and the impending transition towards a UK low carbon economy. Essentially the organisation was determined to acknowledge what internal improvements could be made to adapt to changes in market conditions whilst continuing to provide total building solutions for clients.

VINCI is the third largest construction group in the world. In 2012 the VINCI Group acquired revenue of €38.6 billion, was involved in over 265,000 projects, and employed around 193,000 people across 100 countries. The UK is the second largest operating sector within the VINCI Group outside France, whereby companies such as VINCI Energies, VINCI Facilities, VINCI Park UK, and VINCI Construction UK Limited turn over in the region of £1.9 billion and have approximately 9,000 operatives. In particular, VINCI Construction UK Limited is the national construction company which operates within three core areas (building, civil engineering, and facilities) across five key sectors within the UK non-domestic sector: infrastructure, education, retail, health, and commercial (VINCI, 2014).

From inception to completion the focus of the research project evolved considerably. Originally the research was directed towards discovering ways in which VINCI Construction UK Limited could assist Tesco PLC in achieving their modern environmental objectives, namely *"to become a zero-carbon business by 2050"* (Tesco PLC, 2011). It was believed the broad scope of objectives would highlight potential opportunities to improve environmental performance during project delivery and building operation. Due to economic downturn and resulting changes in the organisation's company strategy and structure, the research expanded its application from a single client perspective to a holistic client perspective incorporating the requirements of varied non-domestic sector clients and project types.

Throughout the research, the Research Engineer (RE) Philip J. Davies worked solely for VINCI Construction UK Limited. Initially the RE worked as a member of VINCI's Retail and Interiors (R&I) Division then subsequently for VINCI's Major Projects Division due to realignment of the organisation's structure. The RE was actively involved in the delivery of three construction projects located within the south of England:

- Project 1 – Large design and build temperature controlled industrial warehouse which contained a three storey office, two small external offices and three internalised temperature controlled chambers for ambient (10 °C), chilled (5 °C) and frozen (-23°C) operating and storage use.
- Project 2 – Large design and build industrial warehouse which contained two small external offices, a single storey mezzanine office and a large chamber for ambient (10°C) operating and storage use.
- Project 3 – Large design and build multi-storey commercial office (13 storeys) which contained a car park, police station, bicycle interchange and multiple retail spaces.

Participation within the on-site construction phase of these projects aided the overall practical application of the research. A number of changes occurred with regards to industrial and academic supervisors throughout the research. Despite the apparent challenges, these changes provided on-going opportunities for the RE to gain new perspectives in terms of alignment of the research objectives and the overall practical application of the research.

1.3 Justification of the Research

There is a need for enhanced awareness along with and a practical approach for initial embodied energy assessment which can be readily adopted by project stakeholders to drive reduced initial embodied energy consumption (Langston and Langston, 2008; Sodagar and

Fieldson, 2008; BIS, 2010; Ko, 2010; Wu et al., 2014). Hence, the rationalisation and key practical benefits of the research project from the contractor's (i.e. industrial sponsor's) perspective are as follows:

- support development of benchmarks, targets and incentives for initial embodied energy reduction;
- support development of initial embodied energy datasets to facilitate future Building Information Modelling (BIM) related projects;
- provide opportunity to increase competitiveness within tender submissions through better prediction and understanding of preliminary energy consumption, costs and overall project life cycle impact;
- provide opportunity to become more adaptive to the UK low carbon economy and more competitive within future environmentally driven markets;
- provide opportunity to lead industry policy and direction from addressing isolated environmental impacts to whole project life cycle impacts;
- provide opportunity to enhance industry reputation through creation of industry best practice with regards to initial embodied energy consumption;
- provide opportunity to decrease the impact of the current Carbon Reduction Commitment (CRC) Energy Efficiency Scheme taxation experienced by projects; and,
- support improved understanding of the significance of individual life cycle phases and the relationship between them.

1.4 Aim and Objectives

The aim of the research was to assess initial embodied energy consumption within UK non-domestic construction projects. The overarching objectives were separated into five which included additional sub-objectives to nurture progressive outcomes and recommendations (i.e. lessons learned) throughout the research. Hence the research objectives were as follows:

[1] Review the current state of art surrounding initial embodied energy consumption within the UK non-domestic sector;

1.1 Review the context and current environmental performance of UK non-domestic construction projects;

1.2 Review the existing methods for assessing initial embodied energy consumption within UK non-domestic construction projects;

1.3 Review the relative significance of individual project life cycle phases within UK non-domestic construction projects;

1.4 Review the existing drivers for contractors to reduce initial embodied energy consumption within UK non-domestic construction projects;

1.5 Review the existing challenges for contractors to reduce initial embodied energy consumption within UK non-domestic construction projects;

1.6 Review the existing opportunities for contractors to reduce initial embodied energy consumption within UK non-domestic construction projects.

[2] Investigate current practices employed by a contractor within UK non-domestic construction projects;

2.1 Investigate the effectiveness of contractor behaviours and current practices towards managing construction phase energy consumption within UK non-domestic construction projects;

2.2 Investigate the potential for contractor current practices to support an initial embodied energy assessment within UK non-domestic construction projects.

[3] Explore a practical framework to support the assessment of initial embodied energy consumption within UK non-domestic construction projects;

   3.1 Develop a practical framework for an initial embodied energy assessment within UK non-domestic construction projects;

   3.2 Explore the effectiveness of the practical framework to assess initial embodied energy consumption within UK non-domestic construction projects.

[4] Examine the practical challenges and opportunities for contractors to address initial embodied energy consumption within UK non-domestic construction projects;

[5] Produce recommendations to industry and stakeholders to tackle the challenges and add value to the opportunities supporting reduced initial embodied energy consumption within the UK non-domestic sector.

The relationship between the objectives and research process, along with the four research papers, is highlighted within Figure 1.1. In addition, the figure illustrates how knowledge was transferred downstream between each research objective.

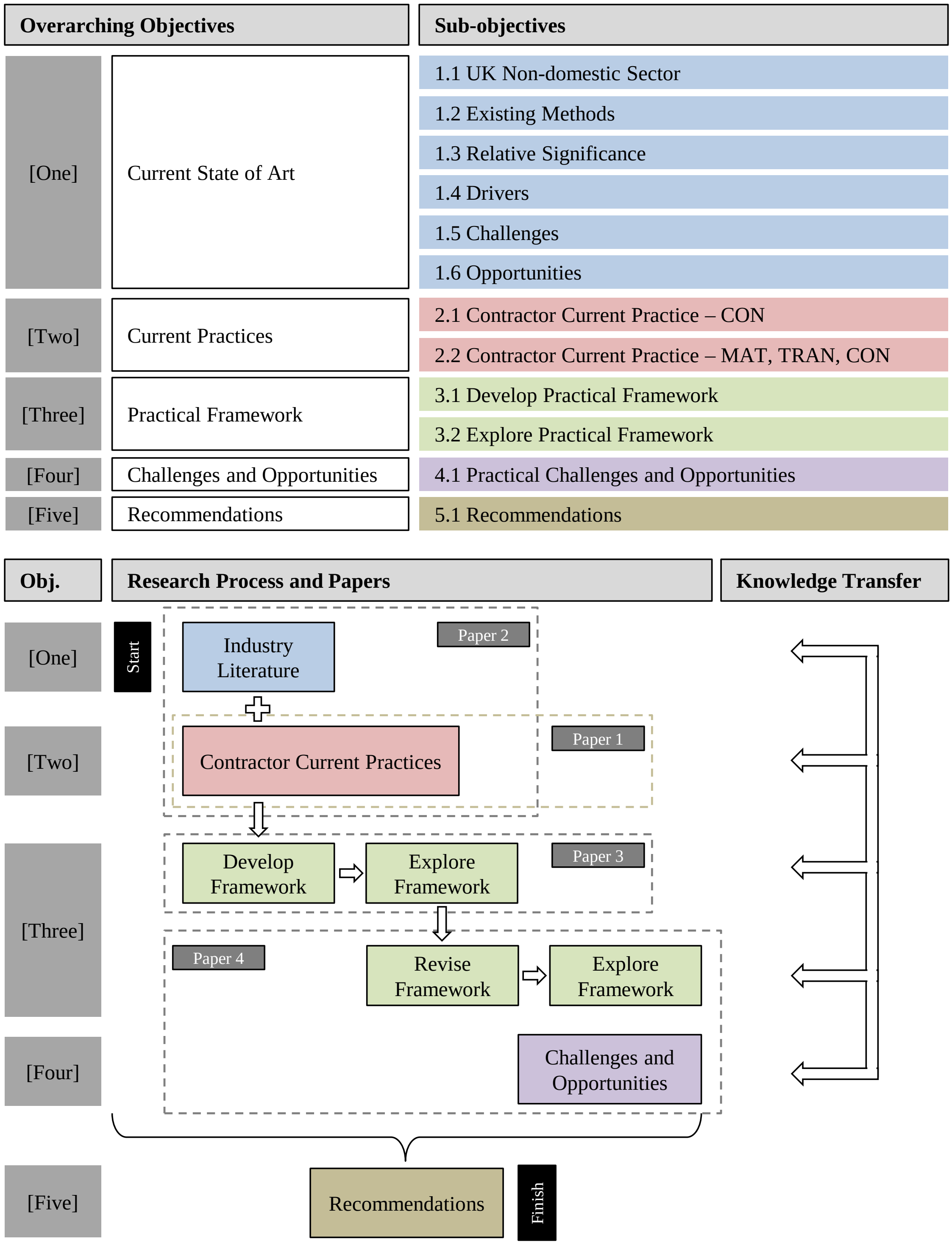

Figure 1.1 Relationship between the research process, objectives and papers

1.5 Novelty of the Research

Existing LCA studies highlighted many difficulties in capturing and assessing project life cycle data, especially transportation and construction phase data (Fay and Treloar, 1998; Gustavsson and Joelsson, 2010; Gustavsson et al., 2010; Halcrow Yolles, 2010; Yung et al., 2013). Hence, due to the unique role of a contractor and the position of the RE, this research project bridged the gap in industry knowledge by highlighting the significance and potential reduction of individual project life cycle phases. Being present on-site during the construction phase of multiple projects provided a unique, detailed account of primary data derived from contractor actions and practices. Consequently, the research has made the following contributions towards the research subject:

- a detailed review of the current practices employed by a contractor to support an initial embodied energy assessment during the construction phase of projects;
- a practical framework designed to assess the initial embodied energy consumption of construction activities, packages and sub-contractors relative individual life cycle phases (i.e. material, transportation, construction phases);
- a detailed account of the practical challenges inhibiting a contractor to acknowledge and deliver reduced initial embodied energy consumption within construction projects;
- a detailed account of the practical opportunities encouraging a contractor to acknowledge and deliver reduced initial embodied energy consumption within construction projects; and
- a series of multi-tiered recommendations for the contractor, industry and direction of future research.

1.6 Overview of the Research Undertaken

The research project adopted an action research methodological approach which was exploited through the implementation of multiple case studies within a large principal contractor based in the UK. Table 1.1 displays the alignment between the research sub-objectives, adopted methods and corresponding research papers; which are presented within Appendix A to Appendix D. Research was undertaken in five stages relating to the overarching objectives. The first stage nurtured a comprehensive industry perspective of the subject through a critical review of industry literature. The second stage studied the contractor perspective of the subject through a critical review of contractor literature, quantitative analysis of project data and qualitative interviews with assorted contractor operatives. The third stage built upon both previous perspectives to acknowledge the capabilities of the contractor through multiple desk studies (industry and contractor literature) and quantitative analysis of project data. The fourth stage developed findings and implications of the research from the contractor perspective through a critical review of all previous outcomes. The final stage provided comprehensive research conclusions and recommendations based upon all previous outcomes.

Table 1.1 Alignment between research sub-objectives, adopted methods and papers

Obj. [a]	No.	Sub-objectives (summarised)	Key Focus	Adopted Methods	Papers[b]
[One]	**1.1**	Review current performance of UK non-domestic sector;	Significance of different project types	Literature Review (industry literature)	**Paper 1**
[One]	**1.2**	Review existing methods for assessing initial embodied energy;	Life cycle assessment (LCA) and life cycle inventory (LCI) methods	Literature Review (industry literature)	**Paper 3**
[One]	**1.3**	Review relative significance of individual project life cycle phases;	Material, transportation and construction impacts per project type	Literature Review (industry literature)	**Paper 2**
[One]	**1.4**	Review existing drivers for contractors;	Policy and legislative, financial and business drivers	Literature Review (industry literature)	**Paper 1**
[One]	**1.5**	Review existing challenges for contractors;	Financial and business, design and technical challenges	Literature Review (industry literature)	**Paper 1**
[One]	**1.6**	Review existing opportunities for contractors;	Financial and business, design and technical opportunities	Literature Review (industry literature)	**Paper 1**
[Two]	**2.1**	Investigate the effectiveness of contractor current practices towards managing construction phase energy performance;	Environmental Performance Indicators (EPI) procedure	Literature Review (industry literature) Literature Review (contractor literature) Case Study (historic project data) Interviews	**Paper 1**
[Two]	**2.2**	Investigate the potential for contractor current practices to support an initial embodied energy assessment;	Programme of works, plant register, bill of quantities, sign-in sheets etc.	Literature Review (industry literature) Literature Review (contractor literature)	**Paper 2**
[Three]	**3.1**	Develop a practical framework;	Combine LCA methods with contractor current practices	Literature Review (industry literature) Literature Review (contractor literature) Case Study (primary project data) Observational Technique	**Paper 3**
[Three]	**3.2**	Explore the effectiveness of the practical framework;	Assess construction package, activity, and sub-contractor impacts	Literature Review (industry literature) Literature Review (contractor literature) Case Study (primary project data) Observational Technique	**Paper 4**
[Four]	**4.1**	Examine the practical challenges and opportunities;	Assess construction package, activity, and sub-contractor impacts	Review of Research Findings	**All Papers**
[Five]	**5.1**	Produce recommendations to address challenges and add value to the opportunities.	Material, transportation and construction impacts	Review of Research Findings	**All Papers**

[a] Obj: Overarching Objective.
[b] Paper: The main focus of each research paper is aligned to each sub-objective.

1.7 Structure of the Thesis

The remainder of the thesis is structured into four chapters. Chapter two details a critical review of industry literature relating to the initial embodied energy drivers, current practice, challenges and opportunities. Chapter three presents the initial methodological considerations and the final methodology adopted to investigate the aim and objectives of the research. Chapter four highlights the research undertaken in order to fully satisfy the aim and objectives of the research. Chapter five defines the key findings and implications of the research from the industrial sponsor perspective, along with the overall conclusions and recommendations for future research. Figure 1.2 displays the relationship between the research objectives, case studies and papers in relation to the structure of the thesis.

Thesis Chapters	Overarching Objectives	Case Studies	Sub-Objectives	Papers
1 Introduction				
2 Literature Review	[One]		1.1	Paper 1
			1.2	Paper 3
			1.3	Paper 2
			1.4	Paper 1
			1.5	Paper 1
			1.6	Paper 1
3 Methodology				
4 Research Undertaken	[Two]	Case Study 1	2.1	Paper 1
		Case Study 2	2.2	Paper 2
	[Three]	Case Study 3	3.1	Paper 3
		Case Studies 4 & 5	3.2	Paper 4
5 Findings and Implications	[Four and Five]		4.1	All Papers
			5.1	All Papers

Figure 1.2 Relationship between the research objectives, case studies and papers in thesis

2 RESEARCH LITERATURE

This chapter reviews the current state of art surrounding improved initial embodied energy efficiency within the UK non-domestic sector. The chapter presents the current performance of the UK non-domestic sector, existing methods for assessing initial embodied energy, the relative significance of individual project life cycle phases, initial embodied energy drivers, current practices, challenges and opportunities for contractors.

2.1 Context

Seemingly an approach which addresses many assorted, intertwined environmental topics (e.g. greenhouse gas emission reduction, and increased energy efficiency) is essential in order to facilitate widespread sustainability throughout industry and wider society (Fay et al., 2000; Vollenbroek, 2002; UNSBCI, 2009; Ramesh et al., 2010). Many environmental topics were considered throughout the initial review of industry literature to improve the context of the research subject (i.e. initial embodied energy). Table 2.1 demonstrates an interdependent, hierarchy relationship between key environmental topics (international and domestic) existing throughout literature. The content and structure signifies that attempts to tackle a specific environmental topic can inexorably lead to changes in other environmental topics upstream and downstream.

Table 2.1 Key environmental topics (upstream and downstream)

No.	Key Environmental Topics	Description and Context[a]
1	**Sustainability**	Refers to a global condition whereby humans and nature can exist in productive harmony by meeting the social, economic and environmental needs of the present without compromising future generations. This condition can be supported through *sustainable development* (WCED, 1987; Pitt et al., 2008; USEPA, 2014a).
2	**Sustainable development**	Refers to improvements undertaken by the construction industry intended to protect human health, enhance quality of life, preserve raw materials and reduce wide environmental impacts and contributions towards *climate change* (Sachs and Warner, 1999; Zimmermann et al., 2005; Asif et al., 2007; Ortiz et al., 2009; Goggins et al., 2010).
3	**Climate change**	Refers to significant long term changes in the Earth's temperature or weather patterns. A major cause of climate change is *global warming* (Met Office, 2014; USEPA, 2014b).

4	**Global warming**	Refers to the on-going rise in temperature near the Earth's surface. Global warming is predominately caused by changes to the atmosphere caused by the release of assorted *greenhouse gases* (Oxford Dictionaries, 2014a; USEPA, 2014b).
5	**Greenhouse gas (GHG)**	Refers to the carbon-based gases that are present within the atmosphere which help regulate temperature and support existence of living organisms on Earth. Apart from water vapour, the most common greenhouse gas is *carbon dioxide* (Oxford Dictionaries, 2014b; WWF, 2014).
6	**Carbon dioxide (CO_2)**	Refers to the gas which is emitted by all life forms when they respire, die or are burned as a fuel. Carbon dioxide is used as the baseline to determine the global warming potential of each greenhouse gas which underlines how long the gas will remain in the atmosphere and how strongly it absorbs *energy* (Oxford Dictionaries, 2014c; USEPA, 2014c).
7	**Energy**	Refers to the power derived from the utilisation of physical or chemical resources. A mixture of petrol, diesel, gas and electrical energy is consumed by a range of different construction industry stakeholders (e.g. manufactures, contractors, clients, end users) in order to develop and benefit from a *project life cycle* (BIS, 2010; Davies et al., 2013a; API, 2014; Oxford Dictionaries, 2014d)
8	**Project life cycle energy**	Refers to the energy consumed during the entire lifespan of a project or building. Project life cycle energy is derived from operational energy (i.e. energy used during building occupier activity) and *embodied energy* (BIS, 2010; RICS, 2010; Davies et al., 2013b; Davies et al., 2014).
9	**Embodied energy**	Refers to the sum of energy inputs (indirect and direct) needed to deliver a particular good or service within the construction process. Embodied energy is derived from recurring (i.e. energy used during refurbishment, renovation and maintenance), demolition (i.e. energy used during on-site deconstruction and disassembly) and *initial embodied energy* (Cole, 1999; Dixit et al., 2010; Davies et al., 2013a; Davies et al., 2015).
10	**Initial embodied energy**	See section 2.2

[a] Description: Content is linked to the following key environmental topic.

2.2 Defining Initial Embodied Energy

Project life cycle energy is comprised from operational and embodied energy. Life cycle operational energy is derived from energy used during building occupier activity whereas life cycle embodied energy is derived from initial, recurring and demolition embodied energy. For the purpose of this research:

- *Initial embodied energy* relates to energy consumed during material (i.e. extraction and manufacture of raw materials), transportation (i.e. transport of materials, plant and equipment, and operatives), and construction (i.e. on-site assembly) life cycle phases up to project practical completion (Cole, 1999; BIS, 2010; RICS, 2010; Dixit et al., 2010).

Figure 2.1 displays the various life cycle phases and activities which impact project life cycle performance, along with the primary focus of the research which relates to material (MAT), transportation (TRAN), and construction (CON) phases.

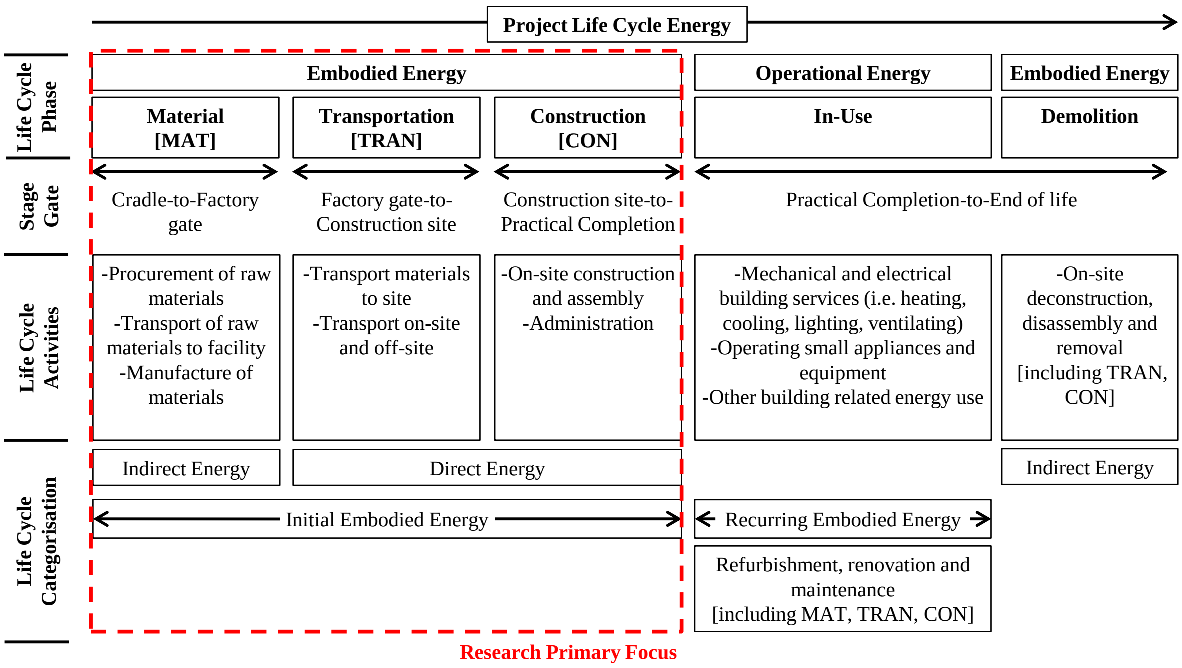

Figure 2.1 Project life cycle energy (after Davies et al., 2014, paper 3)

2.3 Current Environmental Performance

2.3.1 UK Construction Industry

The UK construction industry is complex and fragmented in nature. The industry includes interlinked supply chains and multiple inputs and outputs to additional operating sectors, as highlighted within Figure 2.2 (Latham, 1994; Egan, 1998; SFfC, 2010a). The UK construction industry contains approximately 2.2 million people and represents 8.3% of the UK's gross value added (BIS, 2010).

The construction process, defined as the *"transport, enabling works, assembly, installation and disassembly activities necessary to deliver the service of construction"* Ko (2010), contributes towards significant environmental pollution and consumes a substantial proportion of energy and raw materials (Spence and Mulligan, 1995; Ramesh et al., 2010; Dixit et al., 2010). The process also contributes significantly towards the UK's total CO_2 emission levels as decisions made can notably impact building operational performance (BIS, 2010).

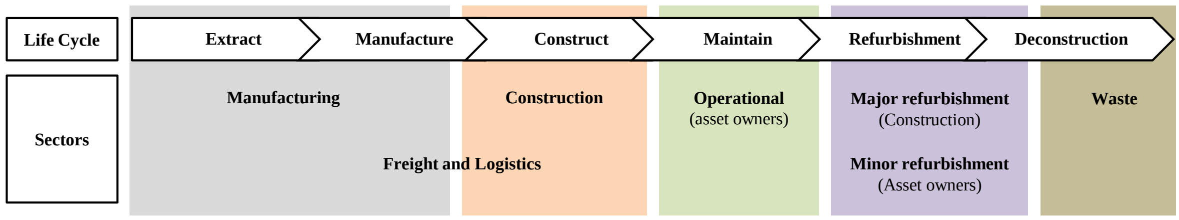

Figure 2.2 Sector ownership during the life cycle of a typical UK construction project (after SFfC, 2010a)

2.3.2 UK Non-Domestic Sector

The UK non-domestic sector accounts for 18% of the UK's total CO_2 emissions (operational and embodied). The sector contains approximately 1.8 million buildings across an array of project types with industrial (23%) and retail (18%) projects responsible for the largest proportion of CO_2 emissions (BIS, 2010; Carbon Connect, 2011). Emissions from this sector have been almost static since 1990 because reductions have been counteracted by increased building floor areas in particular with regards to industrial and commercial office projects (Ravetz, 2008; Carbon Connect, 2011). Reducing CO_2 emissions from the sector by 35% by 2020 could result in a financial cost saving of more than £4.5 billion for the UK economy. Nonetheless, it is expected projects constructed before 2020 will contribute to approximately half of the CO_2 emissions associated with the sector by 2050 (BIS, 2010). Additional information on the construction process and the impact of certain project types within the UK non-domestic sector is presented within paper 1 (Appendix A).

2.4 Existing Methods

There are many methods available for project stakeholders to assess various aspects of sustainable development including initial embodied energy. Methods have evolved over time and adapted to changes in industry or specific project stakeholder policy and direction. Table 2.2 displays a series of methods available to address a wide range of environmental topics at both organisation and project level. An Environmental Management System (EMS) for instance can encourage contractors at organisation level to develop a framework of continuous improvement (plan-do-check-act) which can be applied at project level to help manage construction phase data through enhanced current practices and minimum performance standards for the supply chain (Quazi et al., 2001; EUROPA, 2015; WRAP, 2015a). Alternatively, the Building Research Establishment Environmental Assessment Method (BREEAM) can support contractors to capture and assess project level data from material, transportation and construction phases which can be used to help demonstrate environmental commitment and performance at organisation level (BREEAM, 2010; SFfC, 2010a).

To highlight opportunities to reduce total project life cycle energy, project stakeholders require improved knowledge and assessment of individual project life cycle phases and the relationship between them (Langston and Langston, 2008; Sodagar and Fieldson, 2008; Blengini and Di Carlo, 2010; Optis and Wild, 2010; Davies et al., 2013b). Many previous studies have developed standardised methods for data capture and benchmarking to tackle operational energy use (CIBSE, 2008; Firth et al., 2008; Bagge and Johansson, 2011; Gill et al., 2011; Menezes et al., 2011; Menezes et al., 2012; Cabeza et al., 2014; De Wilde, 2014). However, the concept of addressing initial embodied energy is not as advanced because there is inadequate comprehensive data available, no coherent practical approach and limited incentive for project stakeholders to reduce consumption (Hamilton-MacLaren et al., 2009; BIS, 2010; Dixit et al., 2012; Davies et al., 2013b; Davies et al., 2015). To tackle this challenge, in April 2014 WRAP (Waste & Resources Action Programme) in collaboration with the UK Green Building Council produced the UK's first publically available embodied carbon database for buildings. The database supports practitioners to benchmark project data against detailed comparative data to identify potential carbon savings within future projects. Data is captured in terms of general project information (e.g. name, location), building description (e.g. type, gross floor area), building components assessed (e.g. frame, external walls), data source used (e.g. Inventory of Carbon and Energy, Ecoinvent) and life cycle phases included (e.g. material, construction). In particular life cycle phase data is captured to reflect the international standards for sustainability of construction works (CEN TC 350, see Table 2.2 and Table 2.7) by separating life cycle phases into four stages (product stage, construction process stage, use stage, and end of life stage), which supports the long term application of the database. Although, at present the database only contains 233 registered projects which comprise of either theoretical (132), designed (37) or constructed (64) project data (Arup, 2014; UK-GBC, 2015; WRAP, 2015b; WRAP, 2015c), hence increased capture of project data would further improve the robustness and practicality of the database.

Table 2.2 Series of existing methods available to assess sustainable development

Existing Method	Type	Description and Context
Environmental Management System (EMS)	Standard	- An ISO 14001 accredited Environmental Management System (EMS) is a standard which details an organisation's structure, planning, actions, responsibilities, practices and resources for evolving, applying, completing, reviewing and preserving an environmental policy (Quazi et al., 2001; ISO, 2014); - Can help contractors to reduce operating cost, increase marketability, improve environmental performance, enhance corporate image, and demonstrate compliance with environmental regulation measures (Kuhre, 1995; Ritchie and Hayes, 1998; Tan et al., 1998; Ofori et al., 2002).
CEN TC 350	Standard	- An international standard intended to support the evaluation of the integrated performance of a building over its life cycle (CRWP, 2010; CPA, 2014); - The standard has been produced at a framework (EN 15643-1 and EN 15643-2), building (EN 15978) and product level (EN 15804) to support project stakeholders to measure the sustainability of buildings and construction products (EURIMA, 2012; CPA, 2014); - For more information see Table 2.7.
BREEAM	Assessment	- A form of assessment which evaluates a buildings environmental impact via ten categories (e.g. energy consumption, material selection, waste and pollution management) (BREEAM, 2010); - Can help contractors address transportation and construction phase impacts (CO_2 and energy) through setting targets and capturing data during project development (SFfC, 2010a); - For more information see Table 2.7.

Green Guide to Specification	Assessment	- A form of assessment based upon LCA data used to evaluate the environmental impact of building materials associated with building elements (i.e. roof, external walls, floor) and compared against a ranking system (Fieldson and Rai, 2009; CRWP, 2010; Halcrow Yolles, 2010; Anderson et al., 2011); - Can assist designers to compare, specify and compile material specifications intended for low environmental impact design; without detailing the benefits in terms of energy and CO_2 emission reductions (Fieldson and Rai, 2009; Halcrow Yolles, 2010; Anderson et al., 2011).
Life Cycle Assessment	Assessment	- A form of assessment used to acknowledge the environmental impacts of a product system throughout its entire life cycle (BSI, 2006); - Can help contractors select measurement techniques and indicators to evaluate the environmental performance of their operations (Sodagar and Fieldson, 2008; Ortiz et al., 2009; Doran and Anderson, 2011); - For more information see section 2.4.1.
Carbon Footprinting	Reporting	- Form of reporting used to highlight CO_2 emissions derived from a specific product or an entire organisation based upon LCA data (Sodagar and Fieldson, 2008; Doran and Anderson, 2011); - Can report on direct and indirect impacts (i.e. supply chain) of an organisation (Wiedmann, 2009); - Can help highlight the 'carbon payback' periods for different material, system and technologies removing the reliance upon solely fiscal-based decision making (Smith, 2008).
Energy Profiling	Reporting	- Form of reporting based upon LCA data used to highlight the impacts (embodied and/or operational) associated with individual projects, groups of projects or organisations (Jaccard et al., 1997; Doukas et al., 2007; O Gallachoir et al., 2007; Rasanen et al., 2008); - Can help compare existing and alternative building components and systems in terms of energy efficiency over time (Crosbie et al., 2010; RICS, 2010); - Can help provide information needed to support the refurbishment of the existing building stock within the UK (RICS, 2010).

2.4.1 Life Cycle Assessment

A Life Cycle Assessment (LCA) is a *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"* (BSI, 2006). The International Standards of series ISO 14040 defines the principles of the LCA methodology which includes four distinctive stages: defining the scope and goal; undertaking a life cycle inventory (LCI) analysis; undertaking a life cycle impact assessment; and producing definitive conclusions and recommendations (BSI, 2006; Ortiz et al., 2009). Life Cycle Assessment (LCA) is a common method used to address initial embodied energy consumption, sometimes referred to as a life cycle energy assessment (LCEA).LCA can help identify challenges and opportunities to address initial embodied energy consumption, although applying a LCA within the construction process is a complex, time consuming endeavour involving many multifaceted processes whereby multiple assumptions are commonly required (Treloar et al., 2000; Van Ooteghem and Xu, 2012; Basbagill et al., 2013). Therefore, the practicality and usefulness of LCA data is subject to consideration of key parameters such as the selection of system boundaries, calculation methods and data sources, along with various project factors such as type, scale, location and duration (Lutzkendorf and Lorenz, 2006; Optis and Wild, 2010; Dixit et al., 2012; Davies et al., 2015). Figure 2.3 illustrates the relationship between the different LCA stages and key parameters with regards to initial embodied energy consumption. Further information on the principles of LCA, key parameters, and common assumptions is presented within paper 3 (Appendix C).

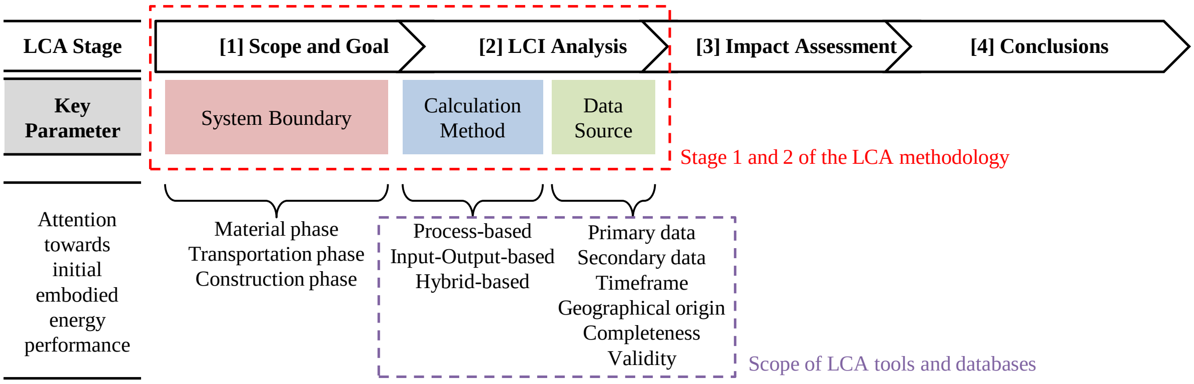

Figure 2.3 Relationship between the different LCA stages and key parameters

The LCI analysis (i.e. stage two) is a reflection of the general quality of an assessment and quantifies the input and output flows for a particular product or process to support the impact assessment (i.e. stage three) (Scheuer et al., 2003; Crawford, 2008). LCA tools and databases are designed to help practitioners quantify the significance of project life cycle impacts to enhance the decision making process (Buchanan and Honey, 1994; Alcorn and Baird, 1996; Gasparatos, 2010; BSRIA, 2011; Gasparatos and Scolobig, 2012; Davies et al., 2013a; Srinivasan et al., 2014). Although, the practical application of existing LCA tools and databases (Table 2.3) is influenced by their inherent calculation methods, data source selections, target audiences, user access and language. Therefore despite their existence, in the future project stakeholders such as contractors may decide to develop internal bespoke methods based upon own current practices to address initial embodied energy consumption due to enhanced knowledge, user-friendliness, resource availability, limited restrictions, and access to primary data (Scheuer et al., 2003; Van Ooteghem and Xu, 2012; Srinivasan et al., 2014; Takano et al., 2014; Davies et al., 2015).

Table 2.3 LCA tools and databases

Name	**Type (Access)**[a]	**LCI Method**	**Description and Context**
ATHENA® Impact Estimator	**Tool** (Limited)	Process	- A process-based tool which, developed by the Athena Sustainable Materials Institute, can facilitate the LCA assessment of individual assemblies or entire buildings and is capable of modelling 95% of the building stock in North America (EUROPA, 2014a); - The tool incorporates regional data such as electricity grid data, transportation modes and distances to calculate a range of impacts (Athena, 2014; Srinivasan et al., 2014); - Can help designers assess the environmental impact of many construction materials, entire buildings or compare assorted building designs using a different metrics (i.e. by life cycle phase or assembly type) (Athena, 2014; EUROPA, 2014a).
Tool for Environmental Assessment and Management (TEAM™)	**Tool** (Limited)	Process	- A process-based tool (also database) which allows LCA practitioners to create and use large databases based upon the operations, products and processes associated with an organisation (EUROPA, 2014a; PWC, 2014); - Can help LCA practitioners describe any industrial system and calculate the associated environmental impacts according to the ISO 14040 series (Curran and Notten, 2006); - Data applicable throughout multiple industries (e.g. construction, manufacture, agricultural, retail, transport).
SimaPro®	**Tool** (Limited)	Process	- A process-based tool (also database) which, developed by PRé Consultants based in the Netherlands, can facilitate a complex LCA assessment of materials, components and systems across multiple life cycle phases (Lapinskiene and Martinaitis, 2013; EUROPA, 2014a; PRé Consultants, 2014; Herrmann and Moltesen, 2015); - Can help support an organisation's carbon footprinting and the production of EPD's (Lapinskiene and Martinaitis, 2013; EUROPA, 2014a; Herrmann and Moltesen, 2015).
Inventory of Carbon and Energy (ICE)	**Database** (Unlimited)	Mixture of process, I-O, hybrid	- An open-access database which contains embodied energy and carbon figures for many construction materials used within the UK derived from publically available historic secondary sourced data (BSRIA, 2011; Doran and Anderson, 2011); - Can assist quantity surveyors to calculate the material phase impact of a project (Fieldson and Rai, 2009; Halcrow Yolles, 2010).
Ecoinvent	**Database** (Limited)	Process	- A process-based database which contains internationally collected LCA data from many industry and public sector services (e.g. agriculture, transport, package materials, construction) developed by Swiss Centre for Life Cycle Inventories (Ecoinvent, 2014; EUROPA, 2014b; Takano et al., 2014);

			- Can help provide high quality, reliable, up-to-date LCA data (Ecoinvent, 2014; Takano et al., 2014); - Data applicable throughout multiple industries (e.g. construction, manufacture, agricultural, chemical, transport).
Carbon Footprint of Products (CFP)	**Database** (Limited)	I-O	- An economic input-output-based database which contains GHG emission data for products developed by the Japan Environmental Management Association for Industry / Advanced Industrial Science and Technology derived from national statistical data (CFP, 2014; Takano et al., 2014); - Can help facilitate detailed carbon footprints and is the first Environmental Product Declaration (EPD) system in Japan (CFP, 2014; Takano et al., 2014).
IBO	**Database** (Limited)	Process	- A process-based database which contains environmental performance (i.e. GWP, acidification potential, non-renewable primary energy demand) of building materials developed by IBO Austrian Institute for Healthy and Ecological Building GmbH derived from industry data (IBO Database, 2014; Takano et al., 2014).
Defra Guide	**Database** (Unlimited)	Mixture of process, I-O, hybrid (assumed)	- An open-access database which contains a series of GHG conversion factors derived from UK government data used to support numerous policies (DEFRA, 2013); - Can help organisations calculate GHG emissions from a range of operations and activities including material, transportation and construction phase impacts (DEFRA, 2013; Davies et al., 2015).
Synergia	**Database** (Limited)	Process	- A process-based database which specifies the weight and GHG emissions for various building materials developed by the Finnish Institute of Environment derived from industrial data (SYKE Finnish Environment Institute, 2014; Takano et al., 2014); - Can help facilitate a detailed carbon footprint of a building structure (SYKE Finnish Environment Institute, 2014; Takano et al., 2014).
GaBi	**Database** (Limited)	Process	- A process-based database (also tool) which contains internationally collected LCA data from industry, associations and public sector services (e.g. retail, education, industrial, plastics, construction) developed by PE International GmbH, Germany (EUROPA, 2014b; GaBi Software, 2014; Takano et al., 2014); - Can help provide unique up-to-date LCA data to commercial users and support international building certification systems (i.e. DGNB, Germany Sustainable Building Council) (GaBi Software, 2014; Takano et al., 2014).

[a] Access: Limited, restricted use due various factors (e.g. free trial period only, data cannot be updated, language barriers, cannot be used for commercial or research purposes); Unlimited, no restrictions for use.

2.5 Relative Significance

The emphasis towards reducing operational energy in contrast to initial embodied energy is apparent within current EU and UK regulatory measures, focus of traditional clients, and common direction within previous research (Bilec et al., 2006; Sartori and Hestnes, 2007; DECC, 2009a; Li et al., 2010; BIS, 2010; Davies et al., 2013b; Janssen, 2014). Typically operational energy represents a greater proportion of project life cycle energy in comparison to initial embodied energy, especially as operational energy increases as building lifespan prolongs (Scheuer et al., 2003; Gustavsson et al., 2010; Van Ooteghem and Xu, 2012). Although as project life cycle impacts are highly interdependent, attempts to reduce the impact of one particular life cycle phase or building aspect (e.g. frame, roof, external walls) may lead to changes in the contribution of other phases. For instance reduced operational energy levels can be achieved through increased thermal mass and wall insulation (Huberman and Pearlmutter, 2008; DECC, 2009a; BIS, 2010; Blengini and Di Carol, 2010; Kneifel, 2010; RICS, 2010; Davies et al., 2013b; Janssen, 2014). Design development can provide economical options to reduce initial embodied energy consumption, though it is viewed as difficult in practice due to insecurity surrounding outcomes from the decision making process (BIS, 2010; RICS, 2010; Monahan and Powell, 2011).

2.5.1 Existing LCA Data

The focus towards producing low energy buildings is expected to influence the relative significance of individual project life cycle phases, in particular initial embodied energy (Chen et al., 2001; Mithraratne and Vale, 2004; Citherlet and Defaux, 2007; Huberman and Pearlmutter, 2008; Blengini and Di Carol, 2010; Rai et al., 2011; Peuportier et al., 2013). Table 2.4 to Table 2.5 present a series of existing LCA studies. From the evidence, the significance of operational energy varied from 40% to 98% of total project life cycle energy whereas initial embodied energy represented 2% to 60%. In some instances, material phase energy represented up to 94% of total project initial embodied energy whereas transportation and construction phase energy represented up to 7% and 6% of the total respectively. Evidently, disparity amongst key parameters (e.g. system boundaries) and project factors (e.g. geographical location) make it difficult for practitioners to conclude similar results, which consequently question the reliability of existing LCA data in order to provide in-depth meaningful comparisons (Treloar et al., 2000; Dixit et al., 2012; Cabeza et al., 2013; Ding and

Forsythe, 2013). The evidence and further supports the need for improved transparency and consistency within LCA studies (Optis and Wild, 2010). Nonetheless, despite the multiple differences, from a broad perspective operational energy was commonly more significant than initial embodied energy and material phase energy was consistently more significant than both transportation and construction phase energy. Further information regarding how material, transportation and construction phase data is typically captured and analysed by LCA practitioners is highlighted within paper 4 (Appendix D).

Table 2.4 Review of existing LCA studies (part 1 of 3) (after Davies et al., 2013b, paper 2)

				Scope and System Boundaries[a]					Data Source[a]			LCI[b]	
Reference	**Location**	**Project Type**	**Results per…**	**Tot OP[a]**	**Tot EE**	**MAT**	**TRAN**	**CON**	**MAT**	**TRAN**	**CON**	**Met'**	Notes & **Key Conclusions**
Adalberth (1997a)	Sweden	Dwelling	Total Project	85% LCE	15% LCE	10% LCE	<1% LCE	1% LCE	-BoQ* -Drawings* -Case studies -Calculations	-Sup' chain data* -Case studies -Calculations	-Sup' chain data* -Case studies -Calculations	Pro*	-LCE equal to 7 years OP -50 year life span -Primary energy **-Offsite MAT can reduce CON**
Aye et al. (2012)	Australia	Apartment	Steel Frame Concrete Frame Timber Frame	60% LCE 68% LCE 67% LCE	40% LCE 32% LCE 33% LCE				-BoQ -Drawings* -National I-O data -SimaPro	-Not captured	-Not captured	Hy	-8 storey multi-residential -63 apartments -50 year life span -Input-output based hybrid -Process data for MAT **-MAT selection is important**
Bansal et al. (2014)	India	Residential	Total Project		2.1-4.3 GJ/m^2				-BoQ -Drawings -Case studies -Calculations	-Not captured	-Not captured	Pro*	-122 houses -Compare masonry construction **-MAT impact varies with building height**
Chang et al. (2012)	China	Educational	Total Project		6.3 GJ/ m^2	90% EE	4% EE	6% EE	-BoQ -Drawings -Case studies -I-O data -Calculations	-Case studies -Google Earth -Calculations	-BoQ -Drawings -National Data -Calculations	Hy	-Process-based hybrid -I-O for MAT **-I-O can only provide rough estimates**
Chen et al. (2001)	China	Residential	Envelope			90.7% EE 91.5% EE	7.4% EE 6.6% EE	1.6% EE 1.6% EE	-BoQ -Drawings* -Case studies -Trade Stats -Calculations	-Case studies -Calculations	-Case studies -Calculations	Pro*	-Energy accounting -40 year life span **-Recycled materials can reduce LCE**
Cole (1999)	Canada	Multi Office	Timber Frame Steel Frame Conc' Frame				8-18 MJ/m2 3-20 MJ/m2 20-120 MJ/m2		-Communication* -BoQ* -Drawings* -Case studies* -ATHENA	-Communication -BoQ -Drawings -Case studies -Assume distance -Assume size -Calculations	-Communication -BoQ -Drawings -Case studies -RS Means data -Calculations	Pro	-CON is measured against total EE **-Operative TRAN is significant**
Cole and Kernan (1996)	Canada	Multi Office	Timber Frame Steel Frame Conc' Frame		4.54 GJ/m^2 5.13 GJ/ m^2 4.79 GJ/ m^2		5-8% LCE		-BoQ* -Drawings* -Case studies -Calculations	-Not captured	-BoQ* -Drawings* -Case studies -Calculations	Pro*	-50 year life span **-Longevity of MAT is important**
Crawford (2008)	Australia	Commercial Commercial Residential	Total Project Total Project Total Project		10.1 GJ/ m^2 8.0 GJ/ m^2 6.9 GJ/ m^2				-BoQ -Drawings -Case studies -Material energy database -National I-O data -Assume data -Calculations	-Not captured	-Not captured	Hy	-I-O based hybrid **-Existing process-based data is inaccurate**

* Data Source: Information not explicitly described or acknowledged (or data calculated) by researcher(s) within literature therefore assumed.

[a] Scope: EE, Embodied energy; OP, Operational energy; LCE, Project life cycle energy (EE + OP); MAT, Material phase energy; TRAN, Transportation phase energy; CON, Construction phase energy.

[b] Life cycle inventory analysis method: Pro, Process-based method; I-O, Input-output-based method; Hy, Hybrid-based method.

Table 2.5 Review of existing LCA studies (part 2 of 3) (after Davies et al., 2013b, paper 2)

Reference	Location	Project Type	Results per…	Scope and System Boundaries[a]: Tot OP[a]	Tot EE	MAT	TRAN	CON	Data Source[a]: MAT	TRAN	CON	LCI[b]: Met'	Notes & **Key Conclusions**
Devi and Palaniappa (2014)	India	Apartment	Total Project	62.7 % LCE	37.3% LCE	32.3% LCE 89.2% EE	5.0 % LCE (TRAN+CON) 7.1% EE	3.7% EE	-BoQ -Drawings -ICE database -National material database -Case studies -Calculations	-Site Visits -Communication -BoQ* -Drawings* -Case studies* -Calculations*	-Site Visits -Communication -BoQ* -Drawings* -Case studies* -Calculations*	Pro*	-96 identical apartments -50 year life span -Primary energy -Demolition 3% of EE and 1% of LCE (inc. CON) -Material TRAN only **-Improved TRAN and CON data needed**
Fay et al. (2000)	Australia	Residential	Total Project		14.1 GJ/m2				-BoQ* -Drawings* -Case studies -Calculations	-Not captured	-Not captured	Hy	-Primary energy -Process-based for MAT quantities -I-O based for MAT energy intensities **-Renovation can offer significant EE savings**
Gustavsson et al. (2010)	Sweden	Apartment	Timber Frame		3.5 GJ/m^2*				-Communication -BoQ -Drawings -Case studies -Calculations	-Communication* -BoQ* -Drawings* -Case studies* -Calculations*	-Estimate	Pro	-Primary energy -Bottom-up analytical technique **-As OP reduces EE becomes more important**
Huberman and Pearlmutter (2008)	Israel	Apartment	Total Project Total Project	40% LCE	60% LCE 8.0 GJ/m^2				-BoQ* -Drawings* -Case studies -Calculations	-Assume distance -Case studies -Calculations	-Estimate	Pro*	-50 year life span **-MAT substitution can reduce LCE**
Kofoworola and Gheewala (2009)	Thailand	Office	Total Project Total Project Total Project	81% LCE	15% LCE 6.8 GJ/ m^2	16.8% LCE	0.6% LCE (TRAN+CON)		-BoQ -Drawings -Case studies -National I-O data -Calculations	-BoQ -Drawings -Case studies -National I-O data -Calculations	-BoQ -Drawings -Case studies -Meter readings -Fuel receipts -Calculations	Hy	-50 year life span -Demolition 0.4% of LCE -I-O based for MAT and TRAN -Process-based for CON **-Combination of measures are required to reduce LCE**
Mithraratne and Vale (2004)	New Zealand	Dwelling	Total Project Total Project Floor Walls Roof		4.4-5.0 GJ/ m^2 34% EE 43% EE 38% EE	94.4% EE	5.6% EE (TRAN+CON)		-BoQ* -Drawings* -National dataset -Case studies -University of Auckland Model	-Case studies* -University of Auckland Model	-Case studies* -University of Auckland Model	Pro*	-100 year life span -Concrete framed house **-Increased insulation can reduce OP**

* Data Source: Information not explicitly described or acknowledged (or data calculated) by researcher(s) within literature therefore assumed.
[a] Scope: EE, Embodied energy; OP, Operational energy; LCE, Project life cycle energy (EE + OP); MAT, Material phase energy; TRAN, Transportation phase energy; CON, Construction phase energy.
[b] Life cycle inventory analysis method: Pro, Process-based method; I-O, Input-output-based method; Hy, Hybrid-based method.

Table 2.6 Review of existing LCA studies (part 3 of 3) (after Davies et al., 2013b, paper 2)

Reference	Location	Project Type	Results per…	Scope and System Boundaries[a]: Tot OP[a]	Scope and System Boundaries[a]: Tot EE	Scope and System Boundaries[a]: MAT	Scope and System Boundaries[a]: TRAN	Scope and System Boundaries[a]: CON	Data Source[a]: MAT	Data Source[a]: TRAN	Data Source[a]: CON	LCI[b]: Met'	Notes & **Key Conclusions**
Monahan and Powell (2011)	UK	Dwelling	Total Project		5.7-8.2 GJ/ m^2				-BoQ -Drawings -ICE database -Ecoinvent -Case studies -SimaPro	-Sup' chain data* -Case studies* -Calculations	-Meter readings -Fuel receipts -Aggregated figures	Pro*	-Primary energy **-Offsite MAT can provide significant LCE reduction**
Rai et al. (2011)	UK	Warehouse	Steel Frame Envelope			31% EE 17% EE			-BoQ -Drawings -ICE Database -SimaPro	-Not captured	-Not captured	Pro*	-25 year life span -Ecotect used for OP **-Design stage can identify prospects to reduce LCE**
Scheuer et al. (2003)	USA	Educational	Total Project Total Project	 97.7 % LCE	7.0 GJ/ m^2 2.2% LCE	2% LCE	0.1% LCE	0.1% LCE	-Communication -BoQ -Drawings -DEAM, -International dataset -Case studies -SimaPro	-Sup' chain data -DEAM -Case studies -Calculations	-Estimate	Pro*	-75 year life span -Demolition 0.2% of LCE -Primary energy **-MAT selection should be made to reduce total LCE**
Thormark (2002)	Sweden	Apartment	Total Project	60% LCE	40% LCE				-BoQ* -Drawings* -Case studies* -Calculations	-BoQ* -Drawings* -Assume distance -Case studies -Calculations	-Not captured	Pro*	-50 year life span **-MAT selection should be based on intensity and recycled content**
Van Ooteghem and Xu (2012)	Canada	Retail	Total Project Roof Frame Found'	91% LCE	9% LCE 52% EE 9% EE 13% EE				-BoQ* -Drawings* -ASHRAE Standard -RS Means data -ATHENA	-Assume through ATHENA	-Assume through ATHENA	Pro*	-50 year life span -Primary energy **-Reduced OP will lead to significant LCE declines**

* Data Source: Information not explicitly described or acknowledged (or data calculated) by researcher(s) within literature therefore assumed.

[a] Scope: EE, Embodied energy; OP, Operational energy; LCE, Project life cycle energy (EE + OP); MAT, Material phase energy; TRAN, Transportation phase energy; CON, Construction phase energy.

[b] Life cycle inventory analysis method: Pro, Process-based method; I-O, Input-output-based method; Hy, Hybrid-based method.

2.6 Drivers

During recent years the European Union (EU) and the UK government have established numerous drivers intended to drive GHG emission and energy consumption reduction within the UK construction industry. Table 2.7 provides a summary of the key policy and legislative drivers which influence organisations to evaluate their environmental impact. Primarily these drivers are directed towards reducing operational energy use, overlooking initial embodied energy (COP 15, 2010; Hernandez and Kenny, 2010; RICS, 2010; Scholtens and Kleinsmann, 2011; Davies et al., 2013a; Davies et al., 2013b). However, in the future a change in focus towards initial embodied energy is expected as operational energy reduces over time owing to improved effective building design (Fieldson and Rai 2009; BIS 2010). Moreover, recent developments within BREEAM and the Carbon Reduction Commitment (CRC) Energy Efficiency Scheme have directly encouraged contractors to develop practices intended to assess a proportion of project initial embodied energy performance (SFfC, 2010a; BREEAM, 2014a; Carbon Connect, 2011; Davies et al., 2013a).

Public awareness surrounding climate change and the desire for green buildings has increased over recent years (Edwards, 1998; Harris, 1999; Halcrow Yolles, 2010). Evidence suggests the public holds governments and large organisations, such as contractors, accountable for addressing climate change and mitigating resultant environmental and social consequences (Eden, 1993; Parmigiani et al., 2011; Peuportier et al., 2013). Hence, in order to adapt to public pressures, increased energy efficiency and reduced CO_2 levels have become widely accepted as common practice within the construction industry (Venkatarama Reddy and Jagadish, 2003). Contractors play an important role towards the creation, delivery and preservation of sustainable development (Sodagar and Fieldson, 2008). Clients are also deemed a significant project stakeholder towards sustainable development (Pitt et al., 2008), though some question their ability to brief effectively and lead by example (Abidin and Pasquire, 2005).

Table 2.7 Key policy and legislative drivers for contractors

Year[a]	Scope[b]	Level[c]	Name	Context
1990	World	Policy	Building Research Establishment Environmental Assessment Method (BREEAM) (the 'scheme')	- Sets the standard for best practice in terms of sustainable design and performance with over one million registered buildings worldwide (BREEAM, 1993; BREEAM, 2014b); - Strongly focused towards addressing operational energy consumption (Halcrow Yolles, 2010; Hernandez and Kenny, 2010) - Material phase impacts are increasingly becoming more significant within the scheme with direct reference to 'embodied carbon' and 'life cycle impacts' within the recent 2011 and 2014 (draft) versions (BREEAM, 2011; BREEAM, 2014a); - The Green Guide to Specification is used to address the environmental impact of materials (DCLG, 2008; CRWP, 2010); - Evidently UK local authorities have enforced planning policies which include minimum BREEAM requirements for future projects (Energy Saving Trust, 2009; Doran and Anderson, 2011; BREEAM, 2014c); - Provides a clear effective standard which makes tackling environmental issues more routine (Morton et al., 2011).
1998	World	Policy	Greenhouse Gas Protocol (GHG Protocol) (the 'protocol')	- Provides an international standard for organisations to assess and understand GHG emissions (SFfC, 2010a; Greenhouse Gas Protocol, 2012a); - Outlines a 'Corporate Standard' designed to support organisations to develop GHG emission inventories, best practice and increase data transparency (Greenhouse Gas Protocol, 2012b); - Used as the basis (i.e. Corporate Standard) for other initiatives such as the Global Reporting Initiative, Carbon Disclosure Project and the Defra Guide (SFfC, 2010a).
2000	World	Policy	Global Reporting Initiative (GRI)	- Aims to make sustainability reporting a standard practice for organisations (Global Reporting Initiative, 2014); - Outlines a framework which includes principles and indicators that organisations can use to address the economic, environmental and social performance of their operations (SFfC, 2010a).
2001	UK	Legislative	Climate Change Levy (CCL) and Climate Change Agreements (CCA)	- Taxation for energy intensive organisations which use electricity, natural gas, petroleum, coal and lignite, and coke (SFfC, 2010a); - Organisations which agree to a CCA can pay reduced levy (90% reduction for electricity and 65% reduction for gas, coal and other solid fuels) if able to meet energy efficiency and GHG reduction targets (HM Government, 2014a); - Construction processes are not covered by CCA's (SFfC, 2010a).
2002	EU	Legislative	Energy Performance of Buildings Directive (EPBD)	- Encourages savings within the built environment via improved energy efficiency and creation of a methodology for capturing and assessing energy consumption (DIAG, 2011); - Supports the need for energy benchmarks for different project types whereby government, designers and clients should lead by example (Hernandez et al., 2008); - The recent recast outlined all new buildings developed from 2021 are expected to be 'nearly zero energy buildings' (i.e. very high energy performance building), with an earlier target date of 2019 for all public authority owned buildings (Hernandez and Kenny, 2010; HM Government, 2014b).

Year[a]	Scope[b]	Level[c]	Name	Context
2003	World	Policy	Carbon Disclosure Project (CDP)	- Aims to use the power of measurement and information disclosure to manage environmental risk (CDP, 2014); - Stimulated the largest worldwide database of environmental data from organisations and cities (SFfC, 2010a; CDP, 2014); - Contractors such as Balfour Beatty, Kier Group, Bouygues, Skanska, Carillion and VINCI have provided data (SFfC, 2010a); - Reporting scope and boundaries are not clearly stated (SFfC, 2010a).
2004	World	Policy	European Network of Construction Companies for Research and Development (ENCORD) Construction CO_2 Measurement Protocol	- Designed to quantity the GHG emissions of an organisation within the construction industry (SFfC, 2010a); - Encourages reporting at company and project level, with a view that organisations will present their data publically (SFfC, 2010a); - Intended to reduce GHG emissions from current and future construction related activities (ENCORD, 2013).
2005	EU	Legislative	EU Emissions Trading Scheme	- Reduces industrial GHG emissions cost-effectively by limiting the total amount of emissions which organisations can produce (European Commission, 2014a); - Encourages organisations to trade emission allowances to provide financial incentive (European Commission, 2014a); - Key considerations are towards energy activities and the production of ferrous metals, minerals (i.e. cement clinker, glass, and ceramic bricks) and pulp (paper, board etc.) (SFfC, 2010a); - Construction processes are not directly affected by the EU ETS (SFfC, 2010a).
2005	EU	Policy	CEN TC 350 Standards (the 'standards')	- On-going work to develop a harmonised approach to measure the embodied and operational impact of construction works, projects and products across the entire life cycle (CRWP, 2010; CPA, 2014); - Anticipated that in the future the UK will use the international standards to regulate environmental measurement as a significant proportion of UK construction products are sourced worldwide (CPA, 2014).
2008	UK	Legislative	The Climate Change Act 2008 (the 'Act')	- Forces UK to ensure that the net carbon account for all six Kyoto anthropogenic GHG's is at least 80% less by 2050 relative to the 1990 baseline (Legislation, 2008); - Mandatory organisational CO_2 emission reporting intended to drive organisations to become more transparent surrounding their environmental performance (BIS, 2010; SFfC, 2010a).
2008	UK	Legislative	Carbon Reduction Commitment (CRC) Energy Efficiency Scheme (the 'CRC')	- Aims to improve energy efficiency through carbon taxation and increased environmental performance transparency (SFfC, 2010a; Carbon Connect, 2011); - Compulsory for organisations (including contractors) consuming more than 6,000 MWh of half-hourly metered electricity (Environmental Agency, 2012); - Organisations are required to report on a wide range of fuel and electricity usage (Energy Team, 2010; Legislation, 2010);Organisations such as supermarkets, hotels, water companies, banks, local authorities, public schools and government departments are targeted (HM Government, 2014c).

Year[a]	Scope[b]	Level[c]	Name	Context
2009	EU	Legislative	Renewable Energy Directive	- Empowers the UK to achieve 15% energy consumption from renewable sources (e.g. wind, solar, geothermal, biomass) by 2020 (DECC, 2009b; Ecolex, 2014).
2009	UK	Legislative	Low Carbon Transition Plan (LCTP)	- Plots how the UK will reduce its GHG emissions by at least 34% by 2020 relative to the 1990 baseline (DECC, 2009a; BIS, 2010); - All non-domestic buildings by 2020 are required to reduce CO_2 emissions by 13% in relation to the 2008 levels, and all new non-domestic public and private sector buildings are required to be zero carbon from 2018 and 2019 respectively (DECC, 2009a; BIS, 2010); - Plan highlighted no reductions required from construction processes in any of the budget periods (2008-12, 2013-17 and 2018-22) (SFfC, 2010a).
2009	UK	Legislative	Low Carbon Industrial Strategy (LCIS)	- Encourages organisations to update the global opportunity surrounding demand for low carbon goods and services (DECC, 2009a; SFfC, 2010a); - The strategy focuses on four key areas: energy efficiency, energy infrastructure, production of low carbon vehicles, and stimulating low carbon business (Renewable Energy Focus, 2014).
2009	UK	Policy	DEFRA Guidance on how to measure and report greenhouse gas emissions (the 'Defra Guide')	- Encourages organisations to measure and publicise their direct, in-direct and supply chain related environmental impacts (CDP, 2009; IEMA, 2010; Carbon Connect, 2011). - Aligns with other international reporting schemes such as the ISO 14064-1 and the Carbon Trust Standard (SFfC, 2010a).
2010	UK	Policy	The Strategic Forum for Construction and the Carbon Trust Action Plan (the 'plan')	- Developed in response to the updated 2008 Strategy for Sustainable Construction report which outlined a 15% carbon emission reduction from construction activity by 2012 (based upon the 2008 levels) (HM Government, 2008); - Encourages the UK construction industry to deliver a reduction in carbon emissions relating to construction activity and associated transport (Ko, 2010); - Focused towards on-site construction and accommodation, transport of materials and waste, business travel and corporate offices (Ko, 2010).
2012	EU	Legislative	Energy Efficiency Directive	- Organisations are expected to use energy more efficiently at all stages of the energy chain (transformation to final consumption) (European Commission, 2014b); - Stimulated national targets for energy efficiency and opportunities to overcome market failures that obstruct efficiency in energy supply and use (European Commission, 2014b).
2014	UK	Legislative	Energy Savings Opportunity Scheme (ESOS)	- Organisations which qualify for the scheme (i.e. employ 250 people or turnover of £50 million) need to assess the energy use (90%) of their buildings, industrial processes and transport requirements every four years (HM Government, 2014c); - Encourages organisations to identify reasonably practicable and cost effective opportunities to reduce energy use whereby the uptake of these opportunities is optional (HM Government, 2014d).

[a] Year: Driver fully established or key stage in development (i.e. initial reporting phase or initial guidelines published).
[b] Scope: Relevance either Worldwide (World), European Union (EU) or United Kingdom (UK).
[c] Level: Legislative, mandatory directive requirement for all countries and organisations included; Policy, voluntary initiative or reporting requirement for all countries and organisations included.

The statement *"if cash is king, carbon must be queen"* emphasised by BIS (2010) appears to reflect the outlook of many contractors. Expected energy price rises are making contractors increasingly aware of the need to reduce energy demand and improve the energy efficiency of their operations (SFfC, 2010a). Table 2.8 summarises the key financial and business drivers which are encouraging contractors to improve their environmental performance and consideration towards initial embodied energy within construction projects. Further information regarding challenges for contractors is provided in papers 1 and 2 (Appendix A and Appendix B).

Table 2.8 Key financial and business drivers for contractors

Key Topic	Context
Cost of energy	- Continual increase in energy prices has forced contractors to improve the energy efficiency of their operations (Okereke, 2007; SFfC, 2010a); - A decrease in secured supply and generation of gas and electricity in the UK is likely to increase energy prices over the next decade (Ofgem, 2009); - As fossil fuels become increasingly scarce contractors will lean towards biodiesel use to power on-site construction operations (Boyer et al., 2008).
Carbon taxation	- Carbon taxation through the CRC has emphasised that the cost of poor energy efficiency is likely to escalate in the future (Carbon Connect, 2011; Sathre and Gustavsson, 2007; Wong et al., 2013).
Supply chain improvements	- Contractors have encouraged supply chains to reduce their energy and carbon levels in order to gain repeat business (SCTG 2002; Bansal and Hunter 2003; Pil and Rothenberg, 2003; BIS 2010); - Environmental Management Systems (EMS) are being used by contractors to screen and select the best well-managed members of the supply chain for a project (Bellesi et al., 2005; Grolleau et al., 2007); - Successful supply chain management can help contractors improve reputation and reduced costs (Wycherley, 1999; Carter et al., 2000; Hervani and Helms, 2005).
Market conditions	- Focus is directed towards developing buildings which consume less energy and carbon levels across multiple life cycle phases (Hoffman, 2006; Okereke, 2007); - Involvement within sustainable development is becoming a marketing tool used by contractors (Fieldson and Rai, 2009); - Successful competition can enable contractors to increase credibility and influence within the development of climate change policy (Batley et al., 2001; Hoffman, 2006; Okereke, 2007; Sodagar and Fieldson, 2008); - Contractors are promoting their environmental commitments for reasons such as increased profit, self-interest, ethical considerations or simply due to increased public pressure (Okereke, 2007).
Client agenda	- Clients such as Tesco, Marks and Spencer's, Debenhams, House of Fraser and John Lewis have all in recent years publically committed towards making huge reductions to their environmental impact from their operations (Okereke, 2007; Fieldson and Rai, 2009).
Corporate Social Responsibility (CSR)	- CSR reporting is used by UK contractors to publish their environmental, social and economic performance in order to improve their value and reputation (SCTG, 2002; Myers, 2005; Jones et al., 2006; Doran and Anderson, 2011); - Despite the increased costs for improved environmental performance contractors are

	hugely compensated by the trust they receive from clients (Okereke, 2007); - Contractors which employ corporate 'greenwash' will not be tolerated by stakeholders (Elkington et al., 1994).

2.7 Challenges

Previous studies have highlighted many challenges for contractors to consider and potentially improve initial embodied energy efficiency within projects. These challenges have been recognised in terms of policy and legislative, environmental and cultural, financial and business, and design and technical categories. Table 2.9 displays common challenges amongst these categories, which relate to: existing regulatory measures; changing environmental conditions; project stakeholder relationships; project management; materials and technologies; and information and tools. Further information regarding challenges for contractors is provided in paper 2 (Appendix B).

Table 2.9 Key challenges for contractors

Key Topics	Cat[a]	Context
Existing regulatory measures	P&L	- Initial embodied impacts are insufficiently represented in existing environmental assessments and regulatory measures (Halcrow Yolles, 2010; Giesekam, et al., 2014);
	P&L	- Achieving current regulatory measures directed towards operational energy improvements could inexorably increase initial embodied energy performance (DECC, 2009a; BIS, 2010; RICS, 2010);
	P&L	- Building Regulation non-compliance levels are growing within the industry (NAO, 2008; Carbon Trust, 2009);
	P&L	- Low energy products and technologies which are not modelled within calculation tools (i.e. SAP and SBEM) cannot be used to present any advantage in complying with Part L of the Building Regulations (BIS, 2010).
Changing environmental conditions	E&C	- Projects are being designed to accommodate current climate conditions which are likely to change in the future (Morton et al., 2011);
	E&C	- Significant changes can reduce quality of workmanship and productivity on-site leading to increased labour and on-site accommodation requirements (Cole, 1999);
	E&C	- Projects cause land disturbance, eco-system alternation, destruction of vegetation, and ground water interference (Cole, 1999).
Project stakeholders relationships	E&C	- Lack of proactive engagement towards climate change is hindering the prospect of increased sustainable development (Hale and Lachowicz, 1998; Hertin et al., 2003; Heath and Gifford, 2006; Morton et al., 2011);
	E&C	- Clients typically emphasise the importance of reducing operational impacts rather than full life cycle impacts (Chen et al., 2001; Pitt et al., 2008; Morton et al., 2011; Giesekam, et al., 2014);
	E&C	- Decisions to confront climate change are normally influenced by practical constraints (i.e. time, cost and regulation) rather than long-term ambitions to develop adaptable buildings (Morton et al., 2011);
	E&C	- Building users accept environmental improvements providing they do not diminish life style (Wines, 2000);

	F&B	- Contractor current practices are not adequate in order to significantly mitigate CO_2 emissions and the effects of climate change (Morton et al., 2011);
	F&B	- Environmental claims made by clients (e.g. zero carbon retail stores) cannot always be justified (Sodagar and Fieldson, 2008);
	F&B	- Some believe manufactures during a price sensitive market have little incentive to develop products, materials and services which are vastly more efficient than its competitors (Hinnells, 2008);
	F&B	- Clients and contractors are disinterested by the long payback periods derived from investment in improved environmental practices (Morton et al., 2011);
	F&B	- Environmental practices are only adopted if they are financially viable (Anderson and Mills, 2002; Sodagar and Fieldson, 2008).
Project management	F&B	- Heavy reliance on imported materials will increase project initial embodied energy levels, cause significant congestion within dense urban environments, and cause projects to suffer from increased transportation costs and poor reliability of deliveries (Chen et al., 2001; BRE, 2003);
	D&T	- Transportation impacts are very procurement and site specific (Halcrow Yolles, 2010);
	D&T	- Obtaining an earlier electrical grid connection is a complex, time-consuming process thus red diesel generators are used to power initial on-site operations (Boyer et al., 2008);
	D&T	- Statutory services do not receive sufficient lead-in from contractors to plan resources for an earlier grid connection (Ko, 2010).
Materials and technologies	F&B	- Reduced operational energy through improved materials and energy efficient building services is more economically attractive for clients than incorporation of renewables (Tassou et al., 2011);
	F&B	- Significant reductions in energy and CO_2 emissions is only likely to be achieved through a vast uptake of renewables (e.g. ground source heat pumps) (Buchanan and Honey, 1994; Liu et al., 2014);
	D&T	- Material or building service choice can significantly impact initial embodied energy performance and need to be selected to satisfy end user requirements (Treloar et al., 2001a; Venkatarama Reddy and Jagadish, 2003; Halcrow Yolles, 2010);
	D&T	- Selecting timber as opposed to concrete or steel can help reduce initial embodied energy performance but cause potential forestry implications (Buchanan and Honey, 1994);
	D&T	- There is an inverse non-linear relationship between operational energy use and insulation thickness whereby there is a direct linear relationship between material phase impact and insulation thickness (Harris, 1999).
Information and Tools	E&C	- Improved information regarding the causes and definitions of key environmental agendas (e.g. global warming and climate change) and strategies to reduce impact (e.g. use of energy efficient design, materials, renewables) are required to assist project decision makers and improve overall public perception (Owens and Driffill, 2008; Whitmarsh, 2009; Morton et al., 2011; Liu et al., 2014);
	D&T	- Due to the complexity of buildings in terms of form, function, life span, and end user requirements there are limited initial embodied energy benchmarks or standardised methods of data collection (Sodagar and Fieldson, 2008; BIS, 2010; Halcrow Yolles, 2010; Ko, 2010; Giesekam, et al., 2014; Janssen, 2014);
	D&T	- Current deficiency of available, robust initial embodied energy data is hindering understanding of how energy is consumed within different building types across various project stages (Hernandez et al., 2008; BIS, 2010; Halcrow Yolles, 2010; Giesekam et al., 2014; Wu et al., 2014; Jang et al. 2015);
	D&T	- Project decision makers do not use exiting data as it is perceived to be dated, hidden within literature, un-validated, fragmented and biased towards successful projects (BIS, 2010; Giesekam, et al., 2014);
	D&T	- Construction phase data is commonly ignored due the shot life span, scale and required data resolution of this phase (Reijnders, 1999; Treloar et al., 1999; Gustavsson and Joelsson, 2010; Van Ooteghem and Xu, 2012; Iddon and Firth, 2013; Pajchrowski et al., 2014);
	D&T	- Material phase data is insufficiently reflected within current industry environmental

		assessment methods (Halcrow Yolles, 2010);
	D&T	- Variation in existing schemes and standards designed to nurture energy and CO_2 emission reduction makes it difficult for contractors to evaluate their true environmental performance and the impact of their decisions (BIS, 2010; IEMA, 2010; Carbon Connect, 2011; Giesekam, et al., 2014; Qingqin and Miao, 2015).

[a] Category: P&L, Policy and Legislative; E&C, Environmental and Cultural; F&B, Financial and Business; D&T, Design and Technical.

2.8 Opportunities

Opportunities for contractors have also been identified within previous studies to support consideration and improvements within project initial embodied energy efficiency. Similar to the previous section (section 2.7), these opportunities are categorised in terms of policy and legislative, environmental and cultural, financial and business, and design and technical challenges. Table 2.10 displays the opportunities common amongst these categories, which relate to the following key topics: existing regulatory measures; changing environmental conditions; project stakeholder relationships; materials and technologies; project management; current practices; project design; and information and tools. Further information regarding opportunities for contractors is provided in paper 2 (Appendix B).

Table 2.10 Key opportunities for contractors

Key Topics	Cat	Context
Existing regulatory measures	P&L	- Drive towards reducing operational energy will increase significance of initial embodied energy performance (Smith, 2008; DECC, 2009a; Doran and Anderson, 2011);
	P&L	- Need for future regulation and industry standards consider initial embodied impacts (energy and carbon) (Ortiz et al., 2009; Halcrow Yolles, 2010);
	F&B	- Improved measures can help contractors receive the correct balance between regulation and environmental protection without leading to increasing costs (SFfC, 2008; Tan et al., 2011).
Changing environmental conditions	E&C	- Constructing buildings with low embodied impacts can help reduce use of raw materials and natural resources (Goggins et al., 2010);
	E&C	- Focus towards promoting sustainable development can help contractors reduce their negative impact on environment and society (Tan et al., 2011; Peuportier et al., 2013; Wong et al., 2013).
Project stakeholder relationships	E&C	- A generation shift (i.e. younger people being more aware) can help contractors address improve environmental compliance and consideration towards climate change (Morton et al., 2011);
	F&B	- Globalisation has encouraged contractors to create vast networks of suppliers and distributors intended to improve the efficiency of material, labour, energy use and reduce cost (Lee 2010; Parmigiani et al., 2011);
	F&B	- Increased cooperative relationships with suppliers can enable contractors to increase their ability to manage environmental issues more effectively (Lee 2010; Parmigiani et al. 2011);

	F&B	- Adopting a green supply chain can help reduce waste, pollution, CO_2 and energy consumption levels in addition to better manage end-product cost and quality (Walker et al, 2008);
	F&B	- Increased cooperative relationships can enable contractors to increase their ability to manage environmental issues more effectively and become future industry leaders (Theyel, 2001; Vachon and Klassen, 2006);
	F&B	- Contractors which deliver higher environmental standards can provide long-term operational cost savings for clients which can help offset capital investment in renewables (Fieldson and Rai, 2009; Halcrow Yolles, 2010; Morton et al., 2011).
Materials and technologies	F&B	- Embodied impacts associated with most renewables (apart from photovoltaic arrays) is relatively low and they can be used to offset project life cycle impacts (Hinnells, 2008; Sodagar and Fieldson, 2008; Halcrow Yolles, 2010);
	F&B	- Renewable technologies can be integrated into the material manufacture phase in order to help reduce material phase energy (Nassen et al., 2007);
	F&B	- Investment in renewable technologies can help organisations reduce cost, increase performance and reduce environmental impacts (Pries, 2003; Kohler et al., 2006);
	D&T	- Material selection can not only influence embodied impacts, but also construction methods, structural form, operational use, maintenance cycles and building life span (Fieldson and Rai 2009; Foraboschi et al., 2014);
	D&T	- Materials such as straw, hemp, earth, prefabricated timber, lime, gypsum can be previously used to reduce the embodied impacts of building structures (Giesekam, et al., 2014).
Project management	F&B	- Reducing project transportation requirements can lead to reduced fuel and delivery costs, increased delivery reliability, reduced cost for parking, and increased profitability for contractors (BRE, 2003);
	F&B	- Employing just-in-time delivery systems and consolidation centres can lead to increased delivery reliability, net cost savings on trade packages, reduced CO_2 emissions from local deliveries, reduced delivery frequency, and reduced on-site material damage (BRE, 2003; Citherlet and Defaux, 2007; Sodagar and Fieldson, 2008);
	F&B	- Use of energy efficient site accommodation, construction plant and reduced reliance on red diesel power generators can lead to significant annual CO_2 and cost savings for contractors (Ko, 2010);
	D&T	- Managing the construction process in a safe, efficient and effective manner, will provide opportunities to save time and cost affiliated to fuel usage and logistics (Sodagar and Fieldson 2008);
	D&T	- The efficient use of plant and equipment during on-site construction can provide savings in fuel use, cost and improve site safety (RICS 2008; Ko 2010);
	D&T	- An earlier connection to the national electricity grid can provide savings in fuel use, security costs, space required for generators, and improve site safety (RICS 2008; Ko 2010);
	D&T	- The use of energy efficient site accommodation can increase operative comfort levels, productivity and reduce absenteeism (Ko 2010);
	D&T	- Contractors can significantly reduce temporary site accommodation energy requirements if the cabins are well designed, positioned and managed (Ndayiragije, 2006);
	D&T	- The efficient use of plant and equipment on-site can be obtained through servicing plant correctly, minimising idling time, using low carbon fuels, choosing plant which is more fuel efficient and reducing the use of oversized machines (Ko, 2010);
	D&T	- Specifying on-site accommodation to include energy efficient measures such as automatic monitoring equipment, improved lighting controls, and voltage optimisation units can provide energy and cost savings for an organisation (Firth et al., 2008; Carbon Connect, 2011; Gill et al., 2011).
Current practices	F&B	- Contractors can nurture the expansion of their business and increase their competitiveness by improving their environmental performance and current practices (Shen and Zhang, 2002; Tan et al., 2011);
	F&B	- Delivery of environmental strategies can improve a contractor’s competence in

		environmental management (Tan et al., 2011);
	E&C	- Investigating the perception of climate change within an organisation can highlight potential opportunities for creating change as well as identify points of resistance (Morton et al., 2011);
	F&B	- Contractors which differentiate themselves and adopt environmental practices can enhance client relationships, company profiles, reputation, and competitive advantages (SCTG, 2004; Hirigoyen et al., 2005; Morton et al. 2011; Janssen, 2014);
	F&B	- Increased demand for sustainable development from clients will improve contractor practices improve linkages within the supply chain (Pitt et al., 2008);
	F&B	- Adopting an Environmental Management System (EMS) can help contractors monitor environmental performance, set objectives, engage with operatives, demonstrate conformity with the supply chain, and facilitate regulatory compliance (Biondi et al., 2000; Nakamura et al., 2001; Quazi et al., 2001; Carbon Connect, 2011).
Project design	D&T	- Prospect to consider both embodied and operational impacts through the principle of bioclimatic design and selection of low carbon materials and energy efficient building services (Gonzalez and Navarro, 2006; Halcrow Yolles 2010; Rai et al., 2011);
	D&T	- Initial embodied energy can be tackled through the incorporation of waste minimisation, reduced material use, increased recycled content and specifying materials with low embodied impact per weight (Harris 1999; Chen et al., 2001; Rai et al., 2011; Giesekam, et al., 2014; Foraboschi et al., 2014; Biswas, 2014; Wu et al., 2014);
	D&T	- Decisions during this stage provide the most cost-effective opportunity to reduce environmental impacts (Goggins et al., 2010);
	D&T	- Decisions during this stage will significantly determine a project's baseline from which the building will begin its operational existence (Scheuer et al., 2003);
	D&T	- If building components are designed to be re-used this would considerably reduce the initial embodied energy performance of a new project (Halcrow Yolles, 2010);
	D&T	- Challenging the design of a building's structure and envelop can significantly improve operational energy efficiency even at the expense of increased initial embodied energy performance (Trusty and Meil, 2000; Scheuer et al., 2003; Foraboschi et al., 2014);
	D&T	- Installing pre-cast and prefabrication materials can reduce initial embodied energy performance in comparison to in-situ and wet-trade options (Halcrow Yolles, 2010).
Information and Tools	P&L	- Improved accurate information regarding climate change from government would help facilitate change and encourage innovation amongst project stakeholders (Morton et al., 2011);
	D&T	- Dynamic building energy simulation models can be used model initial embodied impacts in order to assist decision making by designers and contractors (Rai et al., 2011);
	D&T	- Improved environmental reporting and management can drive organisational behaviour change, identify prospects to enhance energy efficiency, reduce environment impacts, identify new competency requirements, and improve profile (Gray, 2009; Hopwood, 2009; Pitt et al., 2009; DEFRA, 2010; Jones, 2010; Carbon Connect, 2011);
	D&T	- Improved initial embodied energy data can enable design teams to deliver better innovative low carbon designs, clients to create superior benchmarks leading towards improved design briefs, building users to drive change and manage buildings better, and policy makers to target and monitor progress (Sodagar and Fieldson, 2008; BIS, 2010; Goggins et al., 2010; Han et al., 2013);
	D&T	- A national database containing material phase impacts would improve the comparability of designed and completed buildings in order to reduce overall life cycle impacts (Fieldson and Rai, 2009);
	D&T	- Existing databases should be harmonised across all European construction industries via encouraging manufactures to use Environmental Product Declarations (EPDs) to produce standardised material information based upon LCA (Bribian et al., 2011).

[a] Category: P&L, Policy and Legislative; E&C, Environmental and Cultural; F&B, Financial and Business; D&T, Design and Technical.

2.9 Way Forward

This chapter presented the findings from a critical review of industry literature surrounding initial embodied energy consumption. Notably a LCA can help address initial embodied energy consumption though the availability and accuracy of data is dependent upon consideration of key parameters and various project factors. Hence this particular approach was taken forward and explored throughout the research due to its prominence within literature, compatibility with existing open-access databases (i.e. ICE material database, Defra guide) thus being cost neutral, and its overall ability to be modified to produce detailed results. The next chapter presents the adopted research methodology.

3 RESEARCH METHODOLOGY

This chapter provides an overview of the various research methodologies considered in order to undertake the research. The content and overall rationale behind the adopted methodology is presented.

3.1 Research Philosophy and Methods

3.1.1 Research Philosophy

All research begins with a problem which acts as an intellectual stimulus requiring a response (Frankfort-Nachmias and Nachmias, 1996; Blaxter et al., 2006). The research process is the way in which this problem can be examined in order to develop knowledge. The process is derived from seven key stages (i.e. problem, hypothesis, research design, measurement, data collection, data analysis, and generalisation) with each stage influencing, or is influenced by, established research theory and is recurring in nature; the ending of one cycle is the beginning of another (Frankfort-Nachmias and Nachmias, 1996; Davies, 2007; Naoum, 2007).

In particular the research design reflects the decisions made by a researcher with regards to philosophical worldviews, strategies of inquiry and specific methods (Creswell, 2009). Philosophical worldviews (or paradigms) highlight a researcher's general orientation about the world and the nature of research, with characteristics of four different worldviews presented in Table 3.1. Evidently, pragmatism is the most applicable within this research as it focuses on the applications of knowledge to determine practical solutions to problems. Pragmatism encourages the use of a mixture of methods, approaches and techniques to best meet the needs of the researcher (Patton, 1990; Creswell, 2009; Bryman, 2012).

Table 3.1 Comparison between four philosophical worldviews (after Creswell, 2009).

Postpositivism	Constructivism	Advocacy/Participatory	Pragmatism
- Determination - Reductionism - Empirical observation and measurement - Theory verification	- Understanding - Multiple participant meaning s - Social and historical construction - Theory generation	- Political - Empowerment issue-oriented - Collaborative - Change-oriented	- Consequences of actions - Problem-centred - Pluralistic - Real-world practice oriented

The strategy of inquiry (or research strategy) distinguishes the role of theory in relation to research and epistemological (e.g. positivism or interpretivism) and ontological (e.g. objectivism or constructionism) considerations. Epistemology is concerned with the foundations of knowledge, examining the nature of these premises and how they work within the social world, whereas ontology is concerned with the nature of reality, examining the social world as something external to social actors or whether social entities are social constructs built from perceptions and actions (Frankfort-Nachmias and Nachmias, 1996; Bryman and Bell, 2011; Bryman 2012). A quantitative research strategy causes a deductive approach to the relationship between theory and research (i.e. focus on testing theories), incorporates the practices and norms of positivism (i.e. the world is external and objective, researcher is independent, and research is value-free), and views social reality as an objective reality (Blumberg et al., 2005; Bryman and Bell, 2011). It is an inquiry into social and human problems, via the collection and analysis of numbers and statistical procedures (Naoum, 2007; Creswell, 2009). The research upholds a rational, linear process whereby findings are fed back into, or absorbed by, the original theory (Bryman, 1988; Neuman, 2007). The research *"reflects the philosophy that everything in the social world can be described according to some kind of numerical system"* (McQueen and Knussen (2002). Data collected is not theoretical but hard and consistent as it comprises of measurements of the tangible environment (Bouma and Atkinson, 1995). In contrast a qualitative research strategy causes an inductive approach to the relationship between theory and research (i.e. focus on generating theories), rejects the practices and norms of positivism, and views social reality as a constantly shifting emergent property (Bryman and Bell, 2011). The research is primarily concerned with collecting and exploring information in as much detail as possible (Blaxter et al., 2006). The research is based upon a previous set of assumptions about the study of social reality (Bryman, 1988). Researchers use an emerging qualitative approach to collect data within a natural setting sensitive to people and places under consideration, along with data analysis which is inductive and establishes patterns (Neuman, 2007; Creswell, 2009). Researchers express a commitment to viewing actions, events, values, norms, and hidden meanings behind non-obvious features (Bryman, 1988; Have, 2004).

Decisions on the selection of specific methods, approaches and techniques for capturing and analysing data are traditionally influenced by the intrinsic features of either quantitative or qualitative research strategies (Table 3.2). Though, it is not uncommon for strategies to be combined, especially within research intended to inform decisions such as business management research (Burns, 2000; Blaxter et al., 2006; Naoum, 2007; Bryman and Bell, 2011). Mixed methods research enables a researcher to combine elements of both research strategies to progress breadth and depth of understanding and corroboration (Johnson et al., 2007). The strategy facilitates a multi-dimensional view on a subject which helps to reduce the disadvantages of individual approaches or techniques and improve confidence in findings (Fellows and Liu, 2008; Buchanan and Bryman, 2009).

There is an array of assorted approaches and techniques available to undertake a particular research method. Consequently there is no undisputed definitions for these terms, whereby in some instances, the content of specific approaches and techniques overlap (Bryman, 2004; Fellows and Liu, 2008). In line with the requirements of the EngD and the aim and objectives of the research project, the following approaches and techniques are reviewed in within the next section; action research, case study, observational, and interviews.

Table 3.2 Comparison between quantitative and qualitative research methods (after Bryman, 1988; Ragin, 1994; McQueen and Knussen, 2002; Neuman, 2007; Curtis and Curtis, 2011)

Quantitative Research Method	Qualitative Research Method
- Data takes the form of counts, correlations and other statistical formulae; - Methods are perceived as 'data condensers' - Commonly used to study limited characteristics of many examples of something (more than 50); - Emphasises the parsimony of accounts; - Quantitative researchers adopt objective stance; - Focuses on variables and converts them into specific actions during planning stage that occurs before and disconnect from gathering or analysing data; - Quantitative researchers develop techniques to produce data to nurture the transformation from abstract ideas to detailed data collection techniques to exact numerical information; - Quantitative researchers deliberate and reflect on concepts before they gather data; - Research upholds a preparatory role; - Relationship between researcher and subject is distant; - Researcher's stance is as an outsider; - Confirming relationship between theory and research; - Research strategy is structured; - Scope of findings is nomothetic; - Image of social reality is static and external to actor; - Nature of data is hard and reliable.	- Data takes the form of words, images and narratives of all kinds. - Methods are perceived as 'data enhancers' - Commonly used to study multiple characteristics of a few examples (less than 50); - Emphasises the richness of accounts; - Qualitative researcher adopts subjective stance; - Analysis of data is more difficult than quantitative data, requires filtering and arrangement; - Qualitative researchers develop the majority of their concepts during data collection and they re-examine and assess the data and concepts concurrently and interactively; - Research is means to explore actors' interpretations; - Relationship between researcher and subject is close; - Researcher stance is as an insider; - Emergent relationship between theory and research; - Research strategy is unstructured; - Scope of findings is ideographic; - Image of social reality is processual and social constructed by actor; - Nature of data is rich and deep.
- Both types of research methods use two processes: conceptualisation and operationalization; - Both approaches relate to the uniform principle of trying to explore, explain and predict social behaviour.	

3.1.2 Research Methods

3.1.2.1 Action Research

Action research is described as a 'cyclical process' consisting of diagnosis-change-research-diagnosis-change-research (Cummings and Worley, 1993; Brewerton and Millward, 2001). Researchers review the current situation, identify the problem, then introduce and evaluate practical changes intended to improve the situation of an existing or develop a new approach (Greenwood and Levin, 1998; Brewerton and Millward, 2001; Costello, 2003; Naoum, 2007). Action research differs from most social science methods due to the proximity of the researcher in the research process (Rapoport, 1972; Brewerton and Millward, 2001). The researcher attempts to *"close the gap between studying an issue and engaging in social-*

political action to influence the issue" (Neuman, 2011). Whilst remaining objective, there is merit for the researcher to develop partnerships with participants and develop mutually beneficial research aims and objectives to ensure the research project can facilitate long-lasting benefits (Brewerton and Millward, 2001). Though, problems may arise if the researcher does not deliver results that conform to initial expectations or provide closure on a particular issue (McNiff, 2002; Davies, 2007).

Action research can be supported through various approaches and techniques which can be used to a process over varying periods of time to ensure practical findings and improvements (Cohen and Manion, 1989). Typically there needs to be some form of organising or interpreting evidence through an analytical or a conceptual framework (Brewerton and Millward, 2001). Example outcomes from action research could be changing organisation policy, developing a new information management system, or recommending a new approach to assess quality (Naoum, 2007).

Action research is an established method within the fields of business management and information systems. Although since the late 1990s, interest and application of the method within construction has increased as the method compliments the practical problem-solving nature of the industry through identifying issues, introducing changes, and then evaluating the effect of those changes. In particular the method stimulates collaboration between academic researchers and industry practitioners, and also provides structure for inexperienced individuals to undertake applied research within the field (Hauck and Chen, 1998; Azhar, 2007; Connaughton and Weller, 2013). The EngD is a construction research programme that has been based on the principals of action research (Azhar, 2007).

An early example of action research within construction is Cushman (2001) who used the method to explore the application of information systems and communication technologies to add value within construction project teams. Since then many researchers have applied action research within construction. For example, Davey and London (2005) examined the function, current practices and transfer of knowledge within a leading construction company in Australia. Azhar (2007) explored the potential application of action research through a case study which focused on the development and implementation of an information system within a construction organisation. Rezgui (2007) studied the role of knowledge management systems in promoting value creation within the construction industry through the study of four European large principal contractors. Graham et al. (2008) addressed how a leading principal contractor in Ireland integrates knowledge and experience within early project design development to enable potential cost and time savings. Holton (2009) developed a sector sustainability strategy for the UK precast concrete industry in the form of an action plan which detailed a means for stakeholder engagement. Shaw (2010) reviewed innovation management within a large UK principal contactor through the formation of new management processes and online resources. Jang et al. (2011) considered the differences between theoretical approach and practical application of lean construction theory within construction projects. Connaughton and Weller (2013) explored the effectiveness of collaborative working and a new form of insurance for team members within a design and build construction project. Williams (2013) investigated the adoption of renewable energy technology practices within a large UK principal contactor through the creation of a new training programme and improved knowledge share. Evidently all of these previous studies have focused on addressing issues surrounding business management, knowledge management, and information systems within a construction context. Seemingly there is a need for improved information on the suitability of action research to address different issues within a construction context.

3.1.2.2 Case Study

Case studies provide a complex, deeper explanation of the research problem (Yin, 1984; McNeill, 1990; De Vaus, 2001; Blaxter et al., 2006). The approach provides an in-depth study of a single individual, group, event or institution via the use of multiple techniques and methods (surveys, observations, interviews etc.). Designed to study wholes rather than parts and are very useful when it is not possible to exclude external variables (McNeill, 1990; McQueen and Knussen, 2002; Creswell, 2009). The type of case study considered by researchers is commonly influenced by the size and complexity of the bounded case (Yin, 1984; Creswell, 2009), though there are three types of case study which commonly exist. Instrumental case studies focus on a single problem, and then researcher selects one bounded case to illustrate this problem. Collective case studies explore one problem is represented via multiple cases. Generalisation of case study data is improved by the researcher choosing representative cases for the study. Intrinsic case studies focus on a case which represents a unique situation (Bryman, 1988; Stake, 1995; Creswell, 2009). Case studies are suited to situations involving a small number of cases with a large number of variables (De Vaus, 2001). Though a limited supply of cases on a particular problem forces researchers to observe extreme cases in which the process of interest is ‘transparently observable’, allowing case studies to be chosen which replicate emergent theories (Pettigrew, 1998; Huberman and Miles, 2002). Essentially case studies are perceived to be strong in reality as they are drawn from peoples experience and practices. They help researchers demonstrate the complexity of life, develop alternative meanings and interpretations, and act as data sources for future research as their findings can be linked to action and changing practices. However, the complexity of a particular case can make it difficult to analyse, thus case studies only provide theoretical generalisations (Cohen and Manion, 1995; Blaxter et al., 2006; Fellows and Liu, 2008).

3.1.2.3 Observational Technique

Observational techniques are used by researchers to capture quantitative data (Robson, 2002; Have, 2004). The technique allows researchers to study behaviour as it occurs in natural settings and assess the impact of the environment on researched individuals (Frankfort-Nachmias and Nachmias, 1996). The technique is deemed as an additional vehicle of quantitative research whereby the researcher records observations in agreement with a pre-determined schedule and quantifies the subsequent data (Bryman, 1988). Observational techniques fall into three categories: systematic observation; laboratory observation; and participant observation. Systematic observation consists of a researcher observing a group activity or situation without participation. Laboratory observation is implemented when a researcher desires to confront a group with a specified problem or situation. Participant observation is where the researcher is involved within a group activity or situation that is being studied in a natural ‘every day’ setting (Thomlinson, 1969; Stewart, 1998; Robson, 2002; Have, 2004).

3.1.2.4 Interviews

Interviews are used to deliberate a number of topics with an individual or an organised group. Data is produced in the form of a discussion of ideas and experiences. (Thomlinson, 1969; Have, 2004). There are three conditions that are required for a successful interview: accessibility, to obtain information from the interviewee; cognition, the interviewee confidence and understand of what the research concerns; and motivation, for the interviewee to answer the questions fully, (Kahn and Cannell, 1957; Fellows and Liu, 2008). Interviews are undertaken to capture vast targeted information with minimal investment in relation to time and social effort. There are three types of interviews; structured, unstructured, and semi-structured. Structured interviews require researchers to have fixed expectations, use a set answer format and preclude the use of probing questions, all of which eases data capture and analyse. Unstructured interviews are the polar opposite to structured interviews and thus require researchers to be highly skilled as data is difficult to capture and analyse. Semi-structured interviews provide an informal, middle option which enables researchers to use an adaptable answer format and the use of probes (Thomlinson, 1969; McQueen and Knussen, 2002; Have, 2004).

All types of interviews are traditionally undertaken either personal (i.e. face-to-face) or via the telephone. Personal interviews provide researchers the flexibility to control the interview situation, the possibility of modifying an enquiry, and the opportunity to observe participant behaviour. However, the process offers limited standardisation which raises concerns about reliability, can be potentially unsettling for participants due to the presence of the interviewer, and can be very time consuming. Telephone interviews provide researchers with quick, direct access to interviewees to stimulate high response rates and high quality data. Although, the process limits the capture of supplementary information and interviewees may terminate early or be hesitant to discuss certain issues over the phone (Thomlinson, 1969; Frankfort-Nachmias and Nachmias, 1996; McQueen and Knussen, 2002; Have, 2004; Neuman, 2007).

A probe sheet can be used during an interview which contains pre-formulated responses to help a researcher correlate findings (Thomlinson, 1969). The choice of question during an interview is crucial to help translate the research objectives, stimulate data and validate results (McQueen and Knussen, 2002). Close ended questions provide interviewees with a set of predetermined answers whereby the answer which closely reflects their viewpoint is chosen. For open ended questions interviewees are not provided a specified choice (Frankfort-

Nachmias and Nachmias, 1996; Neuman, 2007; Fellows and Liu, 2008). The three corresponding sub-types of questions are outlined within Table 3.3. To improve question responses, researchers commonly use an interview template, issued to the interviewees beforehand, to introduce purpose of the interview and type of questions (Thomlinson, 1969).

Table 3.3 Overview of question sub-types (after Atkinson, 1967; Frankfort-Nachmias and Nachmias, 1996; Neuman, 2007; Fellows and Liu, 2008)

Name	Overview of Question Sub-Types
Opinion	- Sensitive based which may lead respondents to feel more self-conscious and reluctant to answer a question truthfully; - Part of a larger issue of self-presentation as respondents often try to present a positive representation of themselves and the company they work for; - Researchers should only use this type of question when the interviewer has developed a strong rapport with the interviewee if they require strong, honest answers.
Factual	- Questions are indifferent and reassuring; - Designed to extract elicit objective information from respondents; - Most common factual questions are related to the respondent background.
Knowledge	- Used by researchers to discover if respondents know about a particular issue or topic; - Perceived to be threatening as respondents do not want to appear uninformed; - Questions may be more successful if respondents are first asked about factual information.

3.2 Examining Existing Procedure

3.2.1 Practical Considerations

Business management research is regarded as a systematic inquiry within an organisation whose intention is to provide information to overcome managerial problems. The practical consequence of the research can either be theoretical, leading to developments in academic theory (i.e. pure research), or actual, leading to immediate changes in organisation policy, action or performance (i.e. applied research) (Blumberg et al., 2005; Easterby-Smith et al., 2015). The research problem within this research project is essentially a management issue, considering how to capture, assess and potentially reduce initial embodied energy consumption within UK non-domestic construction projects based upon the functions of a principal contractor. To achieve the research aim and objectives, it would be necessary to study internal and external factors which currently influence initial embodied energy consumption within projects and the opinions of individuals working within the sector. This would help to develop practical solutions which can encourage managers within the contractor to improve awareness and application of initial embodied energy consumption within future construction projects.

An essential requirement of the EngD research project is to *"demonstrate innovation in the application of knowledge"* in order to *"develop a solution for a significant and challenging engineering problem within an industrial context"* (CICE, 2014). Hence, the research approach would need to consider the practical application of knowledge, reflect the commercial nature of the industrial sponsor, and provide flexibility with respect to the industrial sponsor's direction and needs. Moreover, the research project is to make a *"significant contribution to the performance of the organisation"* (CICE, 2014) through consideration and potential improvement of key managerial functions such as project planning, organising, co-ordinating and control. Therefore, in this instance, to ensure alignment of both the industrial sponsor and the EngD research project requirements, an applied research approach would be necessary to ensure the development of multiple practical outputs which could be explored within the research project timescale. This approach would enable the research project being separated into smaller focused projects (i.e. research cycles) intended to provide outputs which could be frequently implemented then reviewed within the organisation.

3.2.2 Existing Studies and Methods

To create and rationalise the adopted research methodology, previous studies which presented similar research context and focus to the research project were reviewed. Previous studies supported the use of assorted research methods, approaches and techniques to help produce practical solutions. All reviewed studies provided useful background on the research problem (i.e. content of chapter 2) and insight into applicable research methodology including data sources, such as: energy, contractors, non-domestic sector, life cycle assessment, quantitative (statistical) analysis, and interviews. A sample of reviewed studies is displayed within Table 3.4, which highlights the research scope and methods per study. The mixture of methods used within these studies provided valuable awareness into data capture and assessment. Seemingly, the capture and use of construction project data from case studies was deemed an effective, common approach when exploring energy through the use of a life cycle assessment (LCA). The reviewed studies provided evidence of the different life cycle phases, existing tools and datasets commonly considered when exploring life cycle impacts. Hence, undertaking multiple research cycles would support the capture of construction project data and allow many different aspects of the research subject to be explored within a determined sample. Overall, the review helped substantiate the adopted research methodology, including approaches and techniques, and reinforce the chosen aim and objectives of the research project.

Table 3.4 Sample of reviewed previous studies and methods

Reference	Research Context and Focus[a] E	C	N	L	Q	I	Research Scope	Research Method	Data Source
Cole (1999)	✓	✓	✓		✓	✓	- Initial embodied energy - On-site construction - Alternative building materials - Multi-storey office in Canada	- Case study approach - Telephone interviews and surveys	- R.S. Means Catalogues (database) - Contractor (project data) - ATHENA® Environmental Impact Estimator for Buildings (software tool)
Scheuer et al. (2003)	✓	✓	✓	✓	✓		- Primary energy - Material inventory - Educational building in USA - 75 year building life span - Material, transportation and construction phase	- Case study approach - ISO 14040 life cycle assessment	- Contractor (project data) - DEAM™ (dataset) - Swiss Agency for the Environment, Forests and Landscape (dataset) - SimaPro (software tool)
Sodagar et al. (2008)			✓	✓	✓		- Multiple environmental impact indicators - Embodied and operational impacts - Community hall building in UK - Comparison between different building design	- Case study approach - Carbon footprinting	- Designers and consultants (project data) - Inventory of Carbon and Energy (ICE) (data base) - Ecotect (software tool)
Kofoworola and Gheewala (2009)	✓	✓	✓	✓	✓		- Embodied and operational energy - Office building in Thailand - 50 year building lifespan - Material, transportation and construction phase	- Case study approach - Life cycle energy assessment	- Contractors (project data) - Ministry of Commerce of Thailand (database)
Halcrow Yolles (2010)			✓				- Embodied carbon - Material inventory - Alternative performance design standards - Three office buildings in UK	- Case study approach - Carbon footprinting	- Inventory of Carbon and Energy (ICE) (data base) - UK Building Blackbook (data base) - Manufacturers (project data)
Monahan and Powell (2011)	✓	✓		✓	✓		- Primary energy - Domestic building in UK - Material, transportation and construction phase	- Case study approach - ISO 14040 life cycle assessment	- Contractors, architects, sub-contractors, suppliers and manufacturers (project data) - Inventory of Carbon and Energy (ICE) (data base)
Rai et al. (2011)	✓		✓		✓		- Embodied and operational energy - Material inventory - Alternative envelope design strategies - Distribution warehouse in UK - 25 year building lifespan	- Case study approach - Carbon footprinting	- Inventory of Carbon and Energy (ICE) (data base) - Ecotect (software tool) - Simapro (software tool) - Manufacturers (project data)
Van Ooteghem and Xu (2012)	✓		✓	✓	✓		- Embodied and operational primary energy - Different structure and material types - Five retail units in Canada - 50 year building lifespan	- Case study approach - ISO 14040 life cycle assessment	- ATHENA® Environmental Impact Estimator for Buildings (software tool) - Quick Energy Simulation Tool (eQUEST)

[a] Research Context and Focus: E, Energy; C, Contractors; N, Non-domestic sector; L, Life Cycle Assessment (LCA); Q, Quantitative (statistical) analysis; I, Interviews.

3.2.3 Adopted Methodology

Action research is a *"problem-solving process, appropriate to any situation where specific knowledge is required to address a specific problem"* (Brewerton and Millward, 2001). Action research was selected as the most appropriate research methodology for this research project as it promotes collaboration, provides flexibility in research design, and supports positive change to problems in the form of action (Gill and Johnson, 2002; Herr and Anderson, 2005; Bryman, 2012). The methodology suited the requirements of the EngD and the needs of the industrial sponsor through demonstrating a practical application of knowledge from various approaches and techniques and providing progressive practical outcomes which could be integrated back into the organisation. The following sections highlight consideration towards the research process, strategy, sample and context.

3.2.3.1 Research Process

The research process defines the steps undertaken to achieve the aim and objectives of the research. The research process commenced with a critical review of literature which helped define the research problem and direction (Gill and Johnson, 2002; Creswell, 2009). The cyclic nature of the research methodology (i.e. diagnosing and action planning, action taking, evaluating, and specified learning stages) facilitated five main research cycles, which in turn were explored within the industrial sponsor then reviewed to determine subsequent research cycles. The five main research cycles were supported initially by a critical review of literature (chapter 2) and then concluded with a critical review of all findings (chapter 5). Figure 3.1 displays the alignment between the research cycles and research sub-objectives which defined the research process.

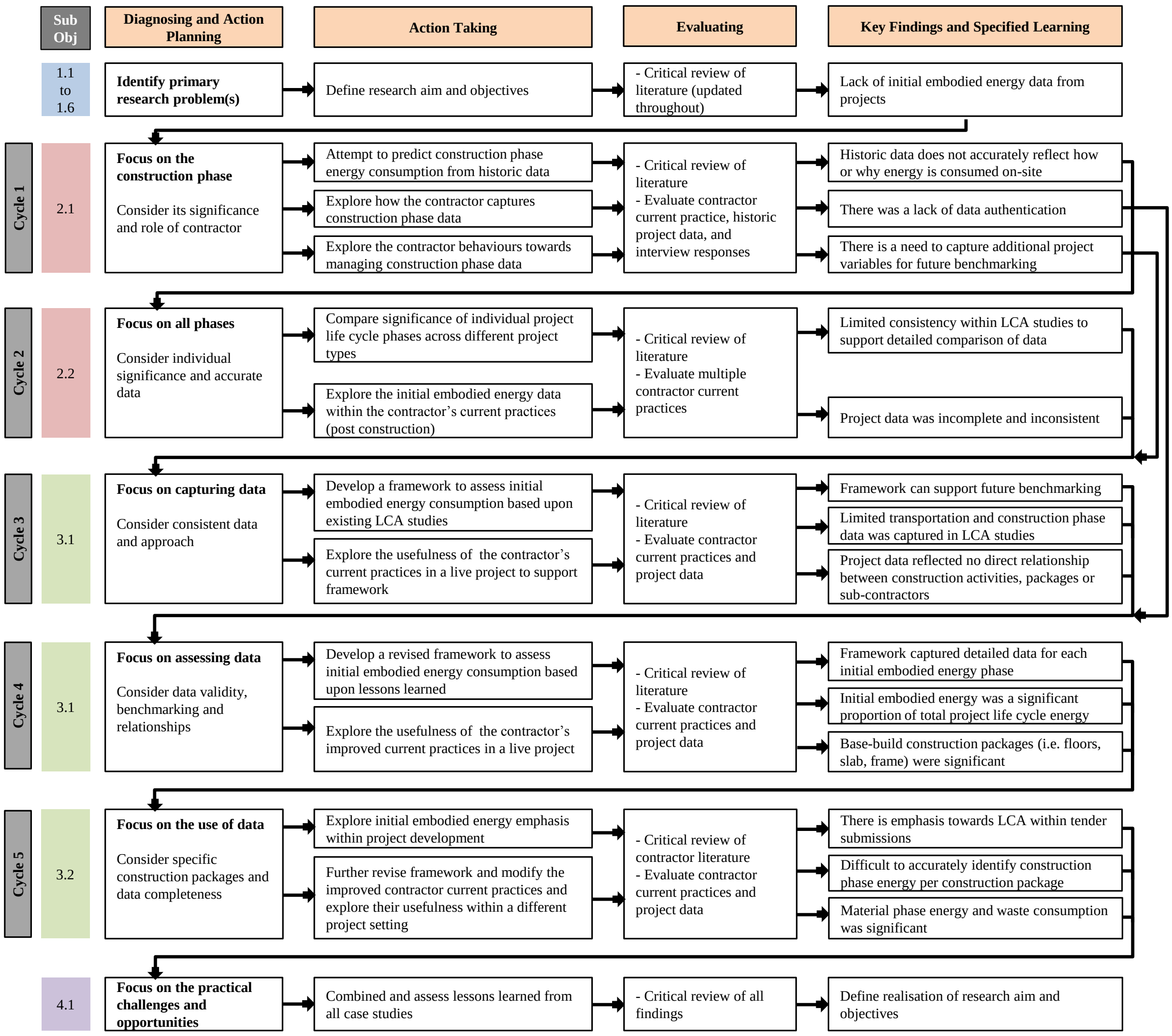

Figure 3.1 Adopted research process

3.2.3.2 Research Strategy

Traditionally action research represents a qualitative research strategy. Although this approach can include a practical blend of both qualitative and quantitative research strategies, adheres to the requirements of a mixed methods research strategy (Greenwood and Levin, 1998; Craig, 2009). Within business management research, a mixed methods research strategy is useful at investigating processual problems, bridging the gap between researcher and practitioner (i.e. manager), and developing relevant, interesting outputs within organisations (Bryman and Bell, 2011). Most action research studies are undertaken through the medium of a case study (Gill and Johnson, 2002). Hence, within this research project a mixed methods research strategy was adopted designed to realise the aim and objectives of the research. This research strategy included various approaches and techniques that were monitored throughout different research cycles to ensure practical findings and improvements. Table 3.5 displays the adopted research approaches, techniques and data analysis methods per research cycle. The methods adopted within the first two research cycles were intended to provide context and foundation to support the methods used within the final three research cycles. Essentially, in line with the aim and objectives of the research, the adopted methods considered: firstly, what actions does the industry and contractor already undertake to capture initial embodied energy consumption data; and secondly, what actions can and should the industry and contractor undertake to reduce initial embodied energy consumption. Hence this intention was reflected within the desire to explore initially secondary data followed by primary data from construction projects. Overall, this research strategy nurtured the development of four research publications which are discussed within the following chapter.

Table 3.5 Summary of adopted research approaches, techniques and data analysis methods per research cycle and paper

	Action Research Methodology				
Research Cycle No.	**Cycle 1**	**Cycle 2**	**Cycle 3**	**Cycle 4**	**Cycle 5**
Research Paper Referred Name	**Paper 1**	**Paper 2**	**Paper 3**	**Paper 4**	**Future Research[d]**
Literature Review[a]	Critical Review of Industry Literature				
Updated Literature Review[b]	✓	✓	✓	✓	
Contractor Literature Review[c]	✓	✓	✓	✓	✓
Case Study	✓		✓	✓	✓
Observational Technique			✓	✓	✓
Interviews	✓				
Regression Analysis	✓				
Spreadsheet Analysis		✓	✓	✓	✓
Content Analysis	✓				

[a] Literature Review: Industry literature focused on all subjects (i.e. drivers, challenges, opportunities, current practices).
[b] Updated Literature Review: Industry literature focused on specific subjects in detail (i.e. LCA methods) due to direction of research cycle.
[c] Contractor Literature Review: Literature and current practices used by the contractor (e.g. programme of works, plant register).
[d] Future Research: See Appendix H.

3.2.3.3 Research Sample Frame

The sample frame (sample) is a fundamental component of any research as it provides a practical means towards data collection and assessment, whilst ensuring a good representation of the population (Eisenhardt, 1989; Fellows and Liu, 2008). Contractors have a vested interest in initial embodied energy consumption and access to transportation and construction phase data due to their significant involvement in project delivery and compliance with current forms of environmental measurement such as Building Research Establishment Environmental Assessment Method (BREEAM) (BREEAM, 2011; Davies et al., 2013a; Davies et al., 2013b; Wong et al., 2013). Hence, the research project investigated the actions and behaviours of a single large principal contractor (i.e. industrial sponsor) based in the UK to facilitate an in-depth perspective of the research subject. It was viewed that the contractor would demonstrate vast awareness of current industry trends due to its overall context, resource availability and reputation within the industry.

3.2.3.4 Research Context

The RE adopted a practical approach towards assessing initial embodied energy consumption from UK non-domestic construction projects, which focused on the calculation and potential reduction of material, transportation and construction phase data. From the review of previous studies (sections 2.4 and 2.5) material selection was highlighted as a significance source of initial embodied energy consumption. During recent years many researchers and UK organisations (e.g. WRAP) produced evidence aimed at project stakeholders, including contractors, to encourage the efficient use of materials during construction to help minimise environmental impacts. Notably this has been targeted through the development of effective waste reduction strategies, waste estimations and records (Yates, 2013; Holmes and Osmani, 2014; WRAP, 2015d; WRAP, 2015e). Based upon literature, examining material selection and developing ways to reduce waste would seemingly help reduce initial embodied energy consumption within construction projects. However, the RE acknowledged to accurately capture and assess waste data throughout the explored research projects within this research project (see below), the RE would have required to compare material quantities within design information (e.g. bill of quantities, design drawings) against material purchase orders from sub-contractors and waste data captured within contractor current practices (i.e. site waste management plan) to evaluate data reliability and validity. Although, as noted within industry literature, a significant amount of time and data management resources would have been required to examine this data within the explored construction projects, especially as data is sensitive in nature (i.e. obtaining purchase orders) and commonly surrounded by uncertainty (i.e. waste estimations and records) (Gottsche, 2012; DEFRA, 2015).

In addition to waste data, at present there is a plethora of material phase data available within literature from previous construction projects which has helped establish sources (e.g. ICE material database) intended to support practitioners to quantify and understand material phase energy (Buchanan and Honey, 1994; Alcorn and Baird, 1996; BSRIA, 2011). Although, there is limited focus towards and available data surrounding transportation and construction phase energy (BREEAM, 2010; Ko, 2010; WRAP, 2015d; WRAP, 2015e). Despite the presence of existing strategic drivers and financial benefits for project stakeholders to improve consideration (see section 2.6), seemingly little is understood with regards to the true significance of transportation and construction phase energy, its key contributors across various project types and construction activities, and its influence across different project life cycle phases. Practitioners have struggled previously to appraise this type of data due to project nature, complexity and timescale (Miller, 2001; Langston and Langston, 2008; DECC, 2010; Ko, 2010; Carbon Connect, 2011), hence the scarce data that is available within literature contains limited relevance and detail to support benchmarks, targets and influence improved energy efficient operations throughout UK non-domestic construction projects (BIS, 2010). Evidently due to their role and position within the supply chain, the RE recognised that contractors have a direct influence and are accountable for construction phase energy (i.e. carbon taxation via the CRC) through the selection of construction methods and fuel source, and can influence transportation phase energy through the selection of materials, plant and equipment and operatives. Hence, the RE focused specifically towards developing a methodology intended to explore all initial embodied energy phases (i.e. material, transportation and construction) to fulfil the gap in industry knowledge regarding the significance of and relationship between different initial embodied energy phases, and how data could be used to inform decisions to reduce energy consumption within future UK non-domestic construction projects. It was highlighted previously in section 2.8 that increased data could help the contractor and wider supply chain improve compliance with current forms of environmental measurement (i.e. BREEAM) and organisation reporting initiatives (i.e. Carbon Disclosure Project), establish alternative energy efficient options (i.e. site accommodation, construction plant), and provide annual carbon and fuel cost savings for contractors and sub-contractors (Dixit et al., 2010; Goggins et al., 2010; RICS, 2010; BRE, 2011; Monahan and Powell, 2011; Tan et al., 2011). Nonetheless, due to its importance within the wider scope of sustainable development, when appropriate waste consumption was also considered by the RE through the use of secondary waste data to estimate total waste consumption per material (i.e. waste stream) within each explored construction project. In particular the RE used the Building Research Establishment’s Waste Benchmark Calculator (referenced within the contractor’s SWMP) to quantify the project type specific waste volumes relative to the building area of each explored construction project (Table 3.6) (BRE, 2012; BRE, 2015a; BRE, 2015b). The RE acknowledged this approach would provide simple calculations of waste consumption and material phase impacts, though uncertainty would surround these values. Nonetheless, the RE recognised the practical framework developed as a result of the adopted methodology (section 4.6.1) could be enhanced to consider primary waste data within future research to improve consideration towards waste consumption and associated impacts.

Table 3.6 Estimated volume of construction waste per material (i.e. waste steam) across each explored construction project

	Project 1	**Project 2**	**Project 3**
Project Type	Industrial Warehouse	Industrial Warehouse	Multi-storey Commercial
Building Area	19,564 m^2	83,675 m^2	50,697 m^2
Material (i.e. Waste Steam)[a]	**Volume (m^3)**[b]	**Volume (m^3)**[b]	**Volume (m^3)**[b]
Bricks	6.75E+01	2.89E+02	2.63E+02
Tiles and Ceramics	2.33E+00	9.97E+00	1.98E+01
Concrete	3.61E+02	1.55E+03	5.63E+02
Inert	4.44E+02	1.90E+03	8.91E+02
Insulation materials (non hazardous)	6.23E+01	2.66E+02	2.50E+02
Metals	1.33E+02	5.68E+02	2.52E+02
Packaging materials	2.01E+02	8.59E+02	1.01E+03
Plasterboard / Gypsum	7.18E+01	3.07E+02	3.60E+02
Binders	3.54E+00	1.51E+01	3.51E+01
Plastic (excluding packaging waste)	4.54E+01	1.94E+02	2.41E+02
Timber	2.90E+02	1.24E+03	1.05E+03
Floor coverings (soft)	2.51E+00	1.07E+01	8.33E+00
Electrical and electronic equipment (non hazardous)	1.57E+00	6.71E+00	1.01E+01
Furniture	8.51E-01	3.64E+00	4.74E-01
Canteen/Office/Adhoc waste	1.07E+02	4.59E+02	1.65E+03
Liquids	5.87E+00	2.51E+01	1.93E+01
Oils	8.96E-02	3.83E-01	3.61E-01
Bituminous mixtures (non hazardous e.g. asphalt)	1.34E+02	5.72E+02	5.73E+01
Hazardous waste	4.83E+01	2.07E+02	3.08E+02
Other waste	1.60E+02	6.86E+02	1.46E+02
Mixed construction and/or demolition waste	5.68E+02	2.43E+03	1.80E+03
Total Waste Consumption per Project	**2.71E+03**	**1.16E+04**	**8.93E+03**
Waste Benchmark (m^3 per 100 m^2)	1.39E+01	1.39E+01	1.76E+01

[a] Waste Stream: materials presented within the BRE Waste Benchmark Calculator.
[b] Volume: values are project type specific waste volumes relative to the respective building area.

3.3 Data Capture and Evaluation

To implement the adopted research methodology data was captured from varied research approaches and techniques. Primarily data was captured and subsequently evaluated through: a review of industry literature and contractor literature (existing or new current practices); a review of case study data supported by observational techniques within live construction projects (primary); a review of case study data from historic construction projects (secondary); and interview responses from contractor operatives. Figure 3.2 summarises the relationship between the overarching objectives of the research project (1 to 4) and the five research cycles, including how data was captured and analysed per cycle.

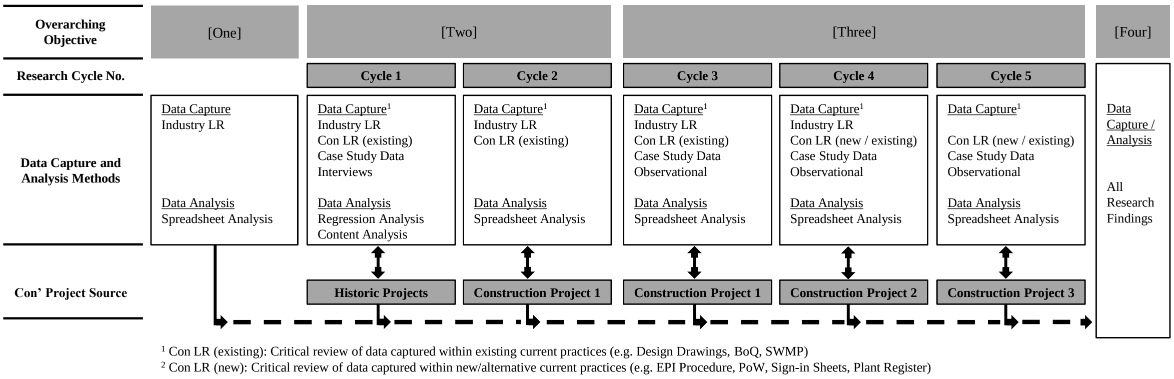

Figure 3.2 Methods used for data capture and analysis relative to research cycles

3.3.1 Development of Critical Review of Literature

Literature was reviewed to determine the context of the research project. Multiple reviews were undertaken which either focused on industry literature, contractor literature or a combination of the two. All reviews were progressively updated throughout the duration of the research in order to maintain awareness of contemporary industry trends and contractor actions.

The first overarching objective required the RE to review the state of art surrounding initial embodied energy consumption within the UK non-domestic sector, which formed the basis of chapter 2. Information and data was reviewed within various sources such as research papers, technical reports, case studies, newspapers, industry magazines and guidance documents. Specifically, research papers (i.e. journal and conference papers) acted as the primary source of information for the industry literature review due to their comprehension, validity and presence within research. Access to academic resources (i.e. library catalogue) and participation within numerous staff development training courses (e.g. 'The Effective

Researcher' and 'What is a Literature Review?') available at Loughborough University provided the RE with sufficient knowledge to discover many online research databases suitable to provide access to research papers. The use of an online research database provided opportunities to undertake detailed searches for applicable research papers by inputting keywords. The keywords used to discover research papers were derived from the RE's knowledge obtained from the preliminary studies (see section 4.1) and involvement within the contractor (i.e. industrial sponsor). The process of discovering research papers was an on-going process to keep up-to-date with new information and research trends. Repeating this process enabled theories, opinions and gaps within industry literature to be identified and correlated against the key themes associated with the first overarching objective. Table 3.7 summarises the overall thought process behind the formation of the industry literature review which helped to support the content validity of subsequent research cycles (see below).

Table 3.7 Formation of the main industry literature review

<table>
<tr><th>Literature Review Process</th><th colspan="2">Literature Review Characteristics</th></tr>
<tr><td>[Step 1]
Key Online Research Database</td><td colspan="2">Question: How and where can research papers be accessed from?
Answer:
Science Direct (http://www.sciencedirect.com)
Elsevier (http://www.elsevier.com)
Taylor & Francis Online (http://www.tandfonline.com)
Emerald Insight (http://www.emeraldinsight.com)</td></tr>
<tr><td>[Step 2]
Key Words (Online Search)</td><td colspan="2">Question: How are relevant Journals and research papers discovered?
Answer:
Energy, Embodied, Life Cycle Assessment, Manufacture, Transportation, Construction, Contractor, Non-domestic, Industrial, Commercial, Operational, Demolition, Recurring, Low (Zero) Energy, Low (Zero) Energy, Environmental Impact, Benchmarking, Model, Framework, Client, Sub-contractor, Supplier, Case Study, Interviews, Operative, Plant, Equipment, Bill of Quantities, Programme of Works, Sign-in Sheets, Drawings, On-site Construction, Construction Activity, Construction Package, Cost</td></tr>
<tr><td>[Step 3]
Key Journals and Papers</td><td>Question: What are the most useful Journals?
Answer:
Automation in Construction
Building and Environment
Building Research & Information
Construction Management and Economics
Energy
Energy and Buildings
Journal of Cleaner Production
Renewable and Sustainable Energy Reviews</td><td>Question: What are the most applicable research papers?
Answer:
- Shen et al. (2005), De Wilde (2014)
- Cole (1999), Van Ooteghem and Xu (2012)
- Fay et al. (2000), Ding (2004)
- Langston and Langston (2008)
- Chen et al. (2001), Rai et al. (2011)
- Scheuer et al. (2003), Dixit et al. (2010)
- Chau et al. (2007)
- Dixit et al. (2012)</td></tr>
</table>

	Sustainable Cities and Society The International Journal of Life Cycle Assessment	- Dakwale et al. (2011) - Optis and Wild (2010)
[Step 4] Sub-Objectives and Key Themes	**Question: What are the sub-objectives? (i.e. focus)** **Answer:** UK Non-domestic sector	**Question: What are the related key themes?** **Answer:** Construction Industry, Europe, United Kingdom, England, Commercial, Hospital, Industrial, Retail, School, College, Office, Warehouse, University
	Existing Methods	Life Cycle Assessment, System Boundaries, Calculation Methods, Data Sources, Assumptions, Process-Based Method, Input-Output-Based Method, Hybrid-Based Method, Building Research Establishment Environmental Assessment Method (BREEAM), Green Guide, Carbon Footprinting, Energy Profiling, CEN TC 350, LCA tools, LCA databases
	Relative Significance	Embodied Energy, Operational Energy, Recurring Energy, Demolition Energy, Material Phase, Transportation Phase, Construction Phase
	Drivers	Policy, Legislation, Financial, Business, Environmental, Cultural, Design, Technical
	Challenges	Policy, Legislation, Financial, Business, Environmental, Cultural, Design, Technical
	Opportunities	Policy, Legislation, Financial, Business, Environmental, Cultural, Design, Technical

Building upon this, throughout the five research cycles further critical reviews of contractor literature were undertaken to improve the practical application of the research. Primarily these reviews examined data from eight current practices which the contractor commonly used to manage their on-site operations within typical UK non-domestic construction projects. The data captured within these eight current practices, summarised in Table 3.8, were deemed to contain initial embodied energy consumption data (e.g. material characteristics, transport vehicle type, transport distances, on-site fuel consumption) suitable for study. Overall, these reviews supported the development of subsequent objectives whereby the relationship between the content of each review, along with each research objective and paper, is presented within Appendix E. In addition to the eight current practices, during the fifth research cycle eleven project tender documents which the contractor commonly used to manage and respond to project tender requirements were reviewed. The purpose of each project tender document is illustrated within Table 3.9, whereby each document was addressed primarily in terms of their consideration towards initial embodied energy consumption and associated data (i.e. material, transportation and construction phase data). Though additional themes previously noted in section 2.1 which relate to initial embodied energy (e.g. life cycle assessment, carbon footprinting, environmental management systems) were also deemed suitable for study.

Table 3.8 Purpose and information characteristics of the contractor's on-site current practices

Current Practice	Purpose and Information Characteristics[3]
Bill of Quantities (BoQ)[1]	Used to coordinate project cost and provide information on material characteristics and specification Information captured once (potential revisions) on MAT type and quantity per sub-contractor
Design Drawings[1]	Used to coordinate project design and provide information on material characteristics and specification Information captured once (potential revisions) on MAT specification, detail and measurement per sub-contractor
Resource Database[1]	Used to document project resources (i.e. operatives, plant, materials) during on-site construction Information captured continuously (e.g. daily, weekly or monthly) on MAT, P&E, OPP values per sub-contractor
Plant Register[1]	Used to document the operational performance of on-site plant and equipment Information captured continuously (e.g. daily, weekly or monthly) on P&E type and quantity per sub-contractor
Environmental Performance Indicator (EPI) Procedure[1]	Used to capture and assess fuel consumption during on-site construction Information captured periodically (e.g. monthly) on fuel type and quantity per sub-contractor
Sign-in Sheets[1]	Used to capture operative man-hours, man-days per sub-contractor Information captured continuously (e.g. daily, weekly or monthly) on OPP values per sub-contractor Used to capture visitor and material transport to and from site Information captured continuously (e.g. daily, weekly or monthly) on transportation type, distance travelled, and fuel type for MAT, P&E, OPP movements per sub-contractor
Programme of Works (PoW)[2]	Used to coordinate the development and delivery of the project Information captured continuously (e.g. daily, weekly or monthly) on construction package and activity duration
Site Waste Management Plan (SWMP)[1]	Used to capture and assess waste consumption during on-site construction Information captured continuously (e.g. daily, weekly or monthly) on MAT waste consumption per sub-contractor Information captured continuously (e.g. daily, weekly or monthly) on transportation type, distance travelled, and fuel type for MAT waste per sub-contractor

[1] Information captured relative to sub-contractor.
[2] Information captured relative to construction package and construction activity.
[3] Provides information regarding: MAT, Material values; P&E, Plant and Equipment values; OPP, Operative values.

Table 3.9 Overview of project tender enquiry documents explored within research cycle 5

Doc No.	Document	Purpose
1	Instructions for Tender	Developed by the client and provided to the contractor (and other bidding contractors) outlining the scope of the project, key requirements and how overall tender responses will be evaluated (i.e. the number, type and weighting of questions).
2	Project Pre-Qualification Questionnaire (PQQ) Response	Developed by the contractor in response to the client's tender questions. The response was used by the client to assess the credentials and capability of the contractor during pre-tender phase.
3	Collaborative Delivery Framework Strategy	Document developed by the client and provided to the contractor (and other bidding contractors) outlining the scope of the new approach towards tender enquiries and applications. This document was used to support the contractor responses to the *PQQ Response* document.
4	Design Management Strategy	Developed by the contractor in order to demonstrate how the contractor planned to deliver the project design through a robust management process and defined assurance plan. This document was used to support the contractor responses to the *PQQ Response* document.
5	Supply Chain Strategy	Developed by the contractor in order to demonstrate how the contractor planned to achieve value-for-money form the supply chain in terms of minimising programme, cost and quality risk. This document was used to support the contractor responses to the *PQQ Response* document.
6	Responsible Procurement Strategy	Developed by the contractor in order to demonstrate how the contractor planned to ensure compliance with the client's responsible procurement policy. This document was used to support the contractor responses to the *PQQ Response* document.
7	Sustainability Strategy	Produced by the contractor in order to demonstrate acknowledgment of the client's sustainability strategy. This document was used to support the contractor responses to the *PQQ Response* document.
8	Environmental Management Strategy	Developed by the contractor in order to demonstrate how the contractor planned to ensure compliance with the client's environmental and sustainable requirements. This document was used to support the contractor responses to the *PQQ Response* document.
9	Environmental and Quality Management Strategy	Developed by the contractor in order to demonstrate how the contractor planned to ensure compliance with the client's environmental and quality requirements. This document was used to support the contractor responses to the *PQQ Response* document.
10	Health and Safety, Environmental and Quality Management Strategy	Developed by the contractor in order to demonstrate how the contractor planned to ensure compliance with the client's health and safety, environmental and quality requirements. This document was used to support the contractor responses to the *PQQ Response* document.
11	Key People Submission	Document developed by the contractor to highlight the competencies, skills and experienced of key staff that the contractor employed to manage the project in order to deliver the expectation of the client. This document was used to support the contractor responses to the *PQQ Response* document.

3.3.2 Development of Construction Project Data

Case studies were undertaken to target the capture and assessment of primary data from three live construction projects and secondary data from twenty-four historic construction projects. Each case study, supported by additional approaches and techniques (e.g. review of literature, observational technique, interviews, data analysis), examined current practices and explored new practices towards initial embodied energy data capture and assessment, based upon the functions of the contractor.

During the final three research cycles, the RE had an active involvement within the delivery of three UK non-domestic construction projects. Non-intrusive participant observation was used to capture primary data from these live construction projects. This method nurtured a detailed account of primary data derived from the contractor's actions and practices and intended to limit the need for post construction reviews with contractor and sub-contractor operatives (Bryman, 1988; Stewart, 1998; Peereboom et al., 1999; Menzies et al., 2007; Monahan and Powell, 2011). The sample of construction projects represented projects that were typical to a contractor of similar size and status. The first construction project (Project 1) was a large design and build temperature controlled industrial warehouse located in the south of England. The project contained a three storey office, two pod offices and three internalised temperature controlled chambers for ambient (10 ºC), chilled (5 ºC) and frozen (-23ºC) operating and storage use. The main building comprised: prefabricated steel structure; composite roof and cladding panels; precast concrete retaining wall; glazed façade (for the offices); 50 dock levellers; multiple air source heat pumps for heating and cooling; and a rainwater harvesting unit to offset toilet flushing and external vehicle wash. The second construction project (Project 2) was a large design and build industrial warehouse located in the south of England. The project contained two pod offices, a single storey mezzanine office and a large chamber for ambient (10°C) operating and storage use. The main building comprised: prefabricated steel structure; composite roof and cladding panels; precast concrete retaining wall; glazed façade (for the offices); 170 dock levellers; multiple air source heat pumps for heating and cooling. The third construction project (Project 3) was a large design and build multi-storey commercial office (13 storeys) located in the south of England. The project contained a car park, police station, bicycle interchange and multiple retail spaces. The main building comprised: two reinforced concrete cores; mixture between a reinforced concrete structure (lower floors) and prefabricated steel structure (upper floors); unitised cladding panels; glazed central atrium; fifteen passenger and goods lifts; multiple air source heat pumps for heating and cooling; a rainwater harvesting unit; and a brown roof to support plantation and wildlife.

Active involvement and correspondence with contractor operatives enabled the RE determine a sample of construction packages, activities and sub-contractors to be investigated within each construction project. The sample was based upon their relative contribution towards project value, duration, operative numbers and quantity of materials used. The relative contribution was defined through a combination of professional judgement (i.e. the RE and industrial supervisors), the use of the pareto principle (i.e. 80% of contribution towards initial embodied energy would derive from 20% of total number of construction packages) and collaboration with the respective project teams; to highlight the most significant construction packages, activities and sub-contractors across each category. In line with the industrial supervisors and industry recommendations (BSRIA, 2011; Jiao et al., 2012), a full assessment of all construction packages, activities and sub-contractors was deemed an unproductive use of the RE's resources and beyond the scope of the research project in terms of providing practical findings that are applicable throughout the entire contractor. Table 3.10 presents an overview of basic project characteristics and explored construction packages across each construction project.

Table 3.10 Characteristics of the explored live construction projects 1-3

Characteristics	Project 1	Project 2	Project 3
Project Type	Industrial Warehouse	Industrial Warehouse	Multi-storey commercial office
Project Duration (Start)	30 weeks (Oct 2011)	30 weeks (Jan 2012)	55 weeks (Mar 2013)
Project Location	South of England	South of England	South of England
Building Area	19,564 m^2	86,000 m^2	50,700 m^2
Explored Construction Packages[1]	Cold Store Walls	-	-
	Dock Levellers	Dock Levellers	-
	Earthworks	Earthworks	Earthworks / Groundworks
	Electrical / Mechanical	Electrical / Mechanical	-
	External Slab	External Slab	-
	External Walls / Roof	External Walls / Roof	-
	Foundations	Foundations	Foundations
	Frame	Frame	RC Frame / Steel Frame
	Ground Floor / Upper Floor	Ground Floor / Upper Floor	-
	Groundworks	Groundworks	(combined in Earthworks)
	Internal Walls	Internal Walls	-
	Main Contractor	Main Contractor	Main Contractor
	Racking	Racking	-
	Refrigeration	-	-
	Retaining Walls	Retaining Walls	-
	Sprinklers	Sprinklers	-
	Syphonic Drainage	Syphonic Drainage	-

[1] Only construction packages that were present and explored within each construction project are displayed (e.g. refrigeration only present in construction project 1 due to project type).

During the first research cycle the RE explored in detail the contractor's Environmental Performance Indicator (EPI) procedure. Through personal correspondence within the contractor and review of the procedure, the RE highlighted 30 non-domestic sector projects that were completed between January 2010 and December 2011 which provided a sample of secondary data relating to on-site energy consumption and management. The sample was limited in number and between a determined timescale due to data availability and time allocated by the RE to undertaken the research cycle; as agreed by the industrial supervisors. From the sample, 24 new-build projects (80%) were fully completed and selected for analysis (see below) as they provided the most comprehensive, comparable data that could be explored. The sample was derived from a mixture of education and healthcare projects, such as: colleges, schools, universities and hospitals. Overall, the sample contained 339 monthly historic EPI data entries consisting of 339 turnover, site area, direct staff, indirect staff values; and 288 electrical energy and 156 red diesel consumption values (i.e. as some projects used a mixture of energy sources). Table 3.11 displays the captured project variables and electrical and red diesel consumption levels across the sample.

Table 3.11 Captured project variables and on-site energy consumption data from the contractor's EPI procedure (Jan 2010 and Dec 2011) (after Davies et al., 2013a, paper 1)

Project Number[a]	Project Type	Loc[b]	Duration	Turnover[c]	Site Area[c]	DS[c]	IS[c]	Electricity[c]	Red Diesel[c]
Project 1	College	SE	10 months	7,200,000	12,000	103	810	274,419	0
Project 2	College	SE	12 months	1,600,000	506	12	176	2,515	0
Project 3	College	SE	15 months	18,600,000	43,750	149	1463	47,784	11,656
Project 4	Hospital	SW	9 months	15,600,000	10,131	79	370	9,710	23,587
Project 5	Hospital	SW	15 months	3,200,000	1,500	49	255	134,976	200
Project 6	Hospital	SE	14 months	1,700,000	432	50	239	39,903	3,592
Project 7	Hospital	NW	18 months	14,200,000	30,000	201	955	205,424	11,462
Project 8	Hospital	NW	16 months	20,900,000	10,000	206	2205	60,000	8,500
Project 9	School	NW	13 months	9,300,000	124,000	90	750	32,909	0
Project 10	School	NW	19 months	20,400,000	12,813	205	1704	39,365	15,249
Project 11	School	SW	10 months	2,000,000	20,920	30	310	58,822	986
Project 12	School	NW	16 months	13,800,000	37,500	232	1568	90,287	82,426
Project 13	School	NW	21 months	22,100,000	29,635	260	1083	263,915	70,631
Project 14	School	NW	15 months	11,400,000	21,165	158	108	189,636	9,224
Project 15	School	SW	7 months	1,100,000	1,400	10	194	559	15
Project 16	School	SE	11 months	2,900,000	1,728	43	316	48,209	205
Project 17	School	Mid	11 months	3,400,000	16,876	46	350	0	28,457
Project 18	School	SW	12 months	10,600,000	42,386	87	725	66,372	35,823
Project 19	School	Mid	15 months	4,800,000	2,744	63	437	72,136	10,500
Project 20	School	SW	12 months	7,300,000	40,000	26	39	94,241	2,951
Project 21	School	Mid	14 months	5,600,000	3,313	76	405	118,497	10,973
Project 22	University	Mid	15 months	17,800,000	14,500	151	1105	794	83,811
Project 23	University	SE	21 months	54,000,000	15,050	384	2746	409,834	20,194
Project 24	University	Mid	18 months	19,000,000	17,406	264	1823	175,436	96,238

[a] Note, all projects are new-build.
[b] Loc; geographical location within England.
[c] Project variables; Turnover (£); Site Area (m^2); DS, Direct Staff (No.); IS, Indirect Staff (No.); Electricity (kWh); Red Diesel (litres).

3.3.3 Development of On-site Current Practices

Based upon the specified learning throughout the research cycles, four on-site current practices (i.e. plant register, programme of works, EPI procedure, and sign-in sheets) were further developed and explored within research cycle four (i.e. Project 2) to improve the capture and assessment of initial embodied energy consumption and aid the validity of findings (section 4.6.2). Each of the on-site current practices was developed at the start and implemented throughout the entire construction phase of the construction project. Various contractor operatives and sub-contractor management at different intervals were required to provide data needed to satisfy the requirements of the developed on-site current practices.

An alternative plant register was developed to collate data received from all sub-contractor specific plant registers. This change intended to reduce inconsistencies in captured data from sub-contractors in terms of data content, detail, legibility and terminology. An example of the developed alternative plant register is displayed within Table 3.12. As construction packages and activities varied in terms of start and completion dates, the transfer of data was an on-going task throughout the entire construction phase of the construction project.

Table 3.12 Example of alternative plant register explored during a live construction project (after Davies et al., 2015, paper 4)

Sub-contractor Name	Construction Package	No. of Operatives and Occupations	No. and Type of P&E used on-site[1]	Duration of P&E use on-site (days)[2]	Duration of P&E use on-site (hours)[2]	P&E fuel capacity (litres)
Main Contractor	Project Management	12 x Supervisors	198 x Skips	150 days	1,200 hours	N/A
			16 x Cabins	150 days	1,200 hours	N/A
			25 x Fuel	150 days	1,200 hours	2,000 liters
Earthworks	Earthworks	1 x Supervisor	11 x Excavators (20t)	120 days	960 hours	400 liters
		22 x Plant Operators	4 x Dumper Trucks (9t)	120 days	960 hours	560 liters
			3 x Bulldozers (6t)	120 days	960 hours	300 liters
			2 x Crusher	120 days	960 hours	130 liters
			1 x Mixer	120 days	960 hours	N/A
			1 x Tractor	120 days	960 hours	400 liters
			21 x Fuel	120 days	960 hours	8,000 liters
Groundworks	Groundworks	3 x Supervisors	4 x Excavator (20t)	135 days	1,080 hours	400 litres
		18 x Plant Operators	4 x Excavator (15t)	135 days	1,080 hours	320 litres
		28 x Labourers	3 x Excavator (9t)	135 days	1,080 hours	200 litres
			4 x Dumper Truck (9t)	135 days	1,080 hours	560 litres
			2 x Roller	135 days	1,080 hours	120 litres
			1 x Telescopic Fork Lift	135 days	1,080 hours	90 litres
			2 x Machine Kerb Lifter	135 days	1,080 hours	N/A
			4 x Petrol Saw	135 days	1,080 hours	N/A
			4 x Skill Saw	135 days	1,080 hours	N/A
			16 x Fuel	135 days	1,080 hours	4,000 litres

[1] Plant and Equipment: t; tonne (size of plant).
[2] Duration: Business days (Monday to Friday); Business hours (8 hours per day).

An alternative programme of works (PoW) was developed which highlighted (i.e. colour coded) each construction package and activity with the corresponding sub-contractor. This simple change intended to help link data received from sub-contractors to specific construction activities; providing a foundation for all other contractor current practices. An example of the developed alternative PoW is displayed within Figure 3.3. As construction packages were awarded to sub-contractors progressively, the inputting of data was an on-going task.

Line	Activity Name	Actual start	Actual finish	Sub-Contractor	Duration
1	Main Contractor	02/01/2012	30/07/2012	Main Contractor	151
6	Bulk earthworks	03/01/2012	30/03/2012	Earthworks	64
10	Piling	23/01/2012	09/03/2012	Foundations	35
12	Concrete pilecaps to new piles	23/01/2012	23/03/2012	Groundworks	45
16	Steework erection	20/02/2012	25/06/2012	Frame	91
176	Drainage works to pond & surrounding area	20/02/2012	04/05/2012	Groundworks	55
237	Concrete rigid paving hardstanding	27/02/2012	15/06/2012	External Slab	80
167	Drainage & Services	27/02/2012	27/04/2012	Groundworks	45
216	Drainage & Services	27/02/2012	25/05/2012	Groundworks	65
21	Vertical cladding	27/02/2012	15/06/2012	External Walls / Roof	80
22	Roof Cladding	27/02/2012	23/07/2012	External Walls / Roof	106
18	Precast Retaining wall & ground beam units	27/02/2012	11/05/2012	Retaining Walls	55
218	Hardcore	12/03/2012	18/06/2012	Earthworks	71
14	Form concrete Hardstanding to perimeter of building	12/03/2012	29/06/2012	External Slab	80
20	Syphonic drainage installation	26/03/2012	15/06/2012	Syphonic Drainage	60
31	Sprinkler Primary pipework installation	02/04/2012	20/07/2012	Sprinklers	80
34	H/L Electrical installation	02/04/2012	16/07/2012	Electrical	76
175	Drainage & services to carpark area	10/04/2012	01/06/2012	Groundworks	39
36	Warehouse floor slab	10/04/2012	06/07/2012	Ground / Upper Floor	64
32	H/L HWS & CWS Installation	16/04/2012	16/07/2012	Mechanical	66
33	H/L Ventilation installation	16/04/2012	06/07/2012	Mechanical	60
27	Dock leveller Ports	23/04/2012	27/07/2012	Dock Levellers	70
239	kerbs & edgings	30/04/2012	15/06/2012	Groundworks	35
37	Racking & sprinkler installation	30/04/2012	10/08/2012	Racking	75
178	Form carparks	14/05/2012	30/07/2012	Groundworks	56
86	Partitions	14/05/2012	01/06/2012	Internal Walls	15
220	Concrete rigid paving hardstanding	21/05/2012	20/07/2012	External Slab	45
209	Concrete rigid paving hardstanding	28/05/2012	27/07/2012	External Slab	45
187	Pour Mezzanine level slab	31/05/2012	01/06/2012	Ground / Upper Floor	2
108	Partitions	06/06/2012	19/06/2012	Internal Walls	10
126	Partitions	06/06/2012	19/06/2012	Internal Walls	10
192	Partitions	14/06/2012	27/06/2012	Internal Walls	10
63	Partitions	02/07/2012	06/07/2012	Internal Walls	5

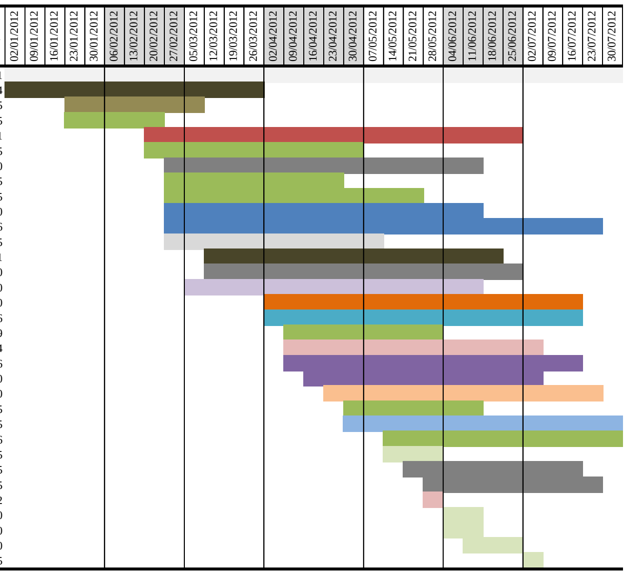

Figure 3.3 Example of an alternative programme of works (i.e. colour coded) during a live construction project

The RE developed an alternative approach towards capturing EPI data which resulted in the production of two new check-sheets and a pro forma. This change intended to improve granularity and validity of captured EPI data (see below). The pro forma was distributed to sub-contractor management and returned on a weekly basis (i.e. week in arrears) via email. The check-sheets highlighted when and what data would be collected from sub-contractors and also verified details of fuel delivery tickets received from the contractor and sub-contractors. Table 3.13 demonstrates the actions undertaken to implement the alternative approach within research cycle 4 (i.e. project 2), whereby an example of the new approach towards capturing EPI data is displayed within Figure 3.4.

Table 3.13 Actions for implementing the alternative EPI Procedure approach during a live construction project

Step	Actions
1.	Produce alternative PoW which highlights (i.e. colour code) sub-contractor responsibilities;
2.	Develop and format pro forma intended to simplify the data requirements of the existing EPI procedure form;
3.	Develop check-sheets which outlines: firstly, when and what data should be collected from each sub-contractor; and secondly, details of fuel delivery tickets received from contractor and sub-contractors;
4.	Forward pro forma to sub-contractors which are active on-site (i.e. data obtained from step. 1) and advise sub-contractors to return the pro forma (once complete), accompanied by fuel delivery tickets, on a weekly basis (i.e. week in arrears);
5.	Once pro forma has returned from sub-contractor, based upon the content, both check-sheets would be used to track and verify data;
6.	Repeat steps 4 and 5 for each active sub-contractor until all data is captured up to project completion.

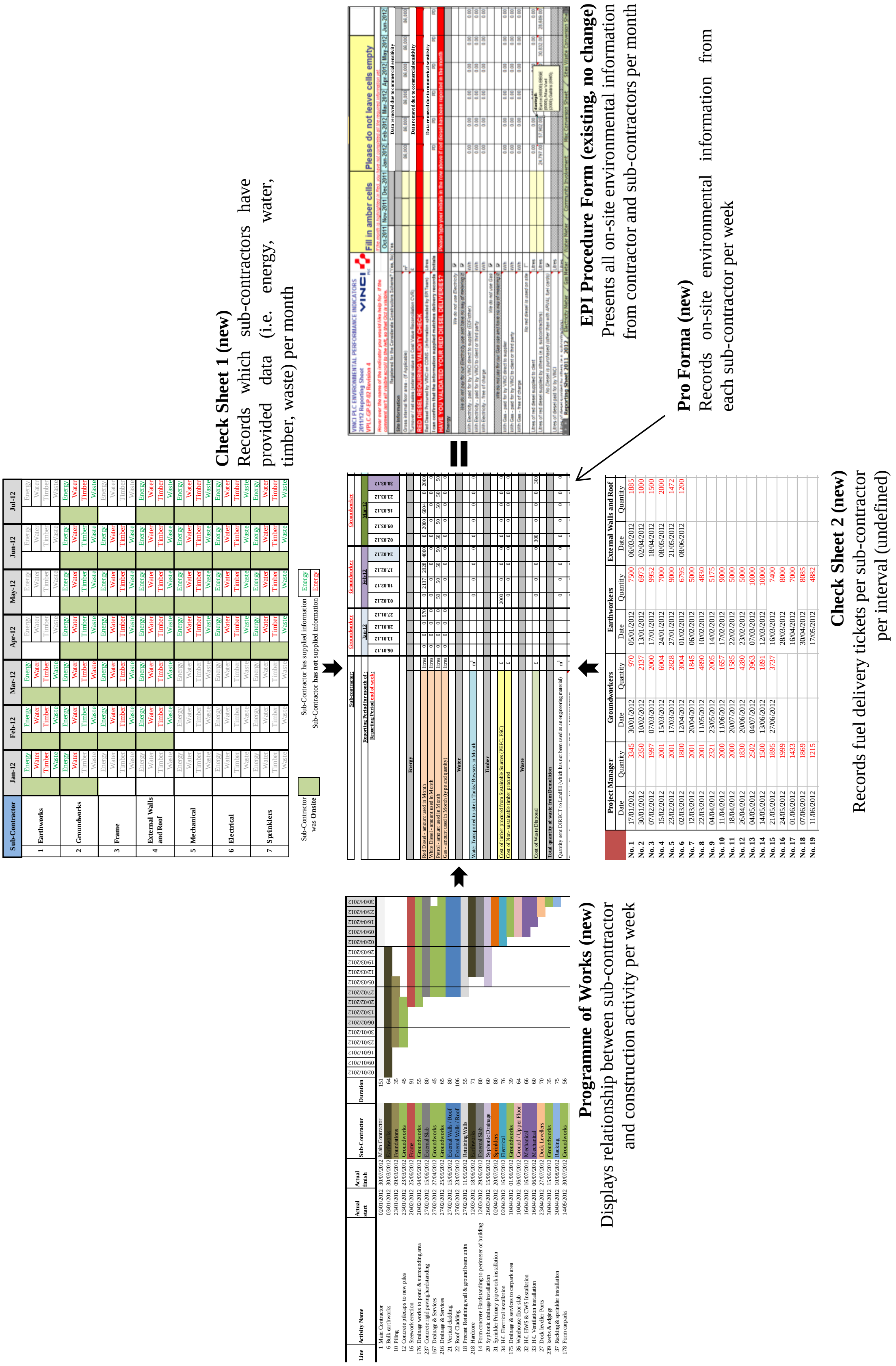

Figure 3.4 Example of the new approach towards capturing EPI data during a live construction project

Three questionnaires in the form of on-site sign-in sheets (Forms ‘A’, ‘B’ and ‘C’) were developed. Form ‘A’ captured material, plant and equipment transportation data in terms of vehicle type, distance travelled, load capacity and intended recipient. Form ‘B’ captured operative transportation data in terms of vehicle type, distance travelled and company name. In contrast Form ‘C’ captured construction phase data such as the number and type of operatives, plant and equipment selected per construction activity. Data was captured during different intervals from three groups of individuals based upon their role, responsibility and involvement within the project. Forms ‘A’ and ‘B’ were filled-in daily by delivery drivers and on-site operatives respectively. Form ‘C’ was filled-in only once by sub-contractor management (i.e. project manager) when the sub-contractor started on-site. Forms ‘A’ and ‘B’ were located within the security gate house at the entrance of the explored construction site accompanied by a brief introduction guide. In terms of Form ‘C’, an introduction guide and a programme of works was provided to each sub-contractor management to link the resources required (i.e. operatives, plant and equipment) for each construction package and construction activity. Figure 3.5 displays and example of the three new sign-in sheets along with the introduction guide which was made available to the operatives to encourage positive response rates and improve face validity of the data capture (see below). More information on the development of the three sign-in sheets is presented within paper 4 (Appendix D).

Philip J. Davies
PROJECT NAME

PROJECT NAME

FORMS Overview

VINCI Construction UK Limited (VINCI) is using the PROJECT NAME as a case-study designed to investigate the project's embodied energy consumption. This document summarises the purpose and content of the multiple 'FORMS' used to aid the embodied energy case-study.

1.0 What is Embodied Energy?

Embodied energy relates to energy consumed during: on-site operations; transportation of materials, plant and operatives; and manufacture of materials, up to project practical completion.

2.0 What information is captured?

The information needed for the case-study is clearly displayed within each of the 'FORMS' A-C. The table below outlines when each form should be filled in, the individual responsible for input and the location of each form.

Form Name	When to fill in Form	Input Required from	Form Location
Form A – Deliveries	Every Delivery / Collection of Materials, Plant and Equipment	Delivery Drivers	Delivery Gate
Form B – Operatives and Visitors	Every day before work commences	Operatives and Visitors	Delivery Gate
Form C – Resource Forecast	Once during Pre-let Meeting (Form Y Stage)[1]	Sub-contractor Management	Site Office

[1]Please note, as this information is crucial additional checks / updates may be required during project progression.

3.0 How does it work?

Generally embodied energy is categorized into the following headings: Manufacture, Transportation and On-site Construction, whereby the 'FORMS' A-C intend to capture the latter two headings. Adding the information gathered from the 'FORMS' with monthly 'Environmental Performance Sub-Contractor Reports'[2] (issued separately) will allow VINCI to accurately calculate the energy consumption per sub-contractor, construction package and element.

4.0 Why is this important to VINCI?

Improving VINCI's awareness of embodied energy can stimulate the following advantages:

- Enhance industry reputation and improve Corporate Social Responsibility (CSR);
- Aid client and supply chains to re-engineer environmental targets and project performance;
- Develop embodied energy benchmarks (sub-contractor, package, element performance etc.) to advance future project performance;
- Stimulate low-energy best practice to reduce overall project environmental impact;
- Decrease project Carbon Reduction Commitment (CRC) tax impact (currently £12 per tonne of CO_2 produced);
- Increase competitiveness within tender submissions via predicting project energy consumption;
- Improve understanding of relationship between manufacture, transportation and on-site energy consumption;
- Provide industry with innovative data suitable to intensify the 'zero-carbon definition' debate;
- Potential to become more competitive in future 'embodied energy' markets.

[2]'The Environmental Performance Sub-Contractor Report' is returned by each sub-contractor on a monthly basis outlining their environmental performance on-site with respect to the following headings: energy, water, timber and waste consumption.

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5.0 Form filling in guidance

This section outlines the most common difficulties when filling in each of the respective FORMS.

5.1 FORM A – Delivery / Collection Sign In Sheet

Information Required	Guidance
Main Delivery Item(s)	If PLANT provide as much detail as possible (name, type, model no. etc.) If MATERIAL specify generic name (insulation panels, steel frame, drainage pipework etc.) If delivery contains multiple small-sized objectives group and provide generic name (sprinkler pipe work etc.)
Intended Recipient Name	Ensure this is filled in (if unknown fill in as much information relative to 'Main Delivery Items')
Vehicle Type	Specify generic name
Vehicle Origin	Specify the origin of the vehicle transporting the load (i.e. beginning of the journey)
Distance Travelled	If unknown ensure information relative to 'Travel From' is filled in correctly
Vehicle Load Capacity	If unknown ensure information relative to 'Vehicle Type' is filled in correctly
Proportion of Load	Estimate approximate percentage of delivery items (Delivery of concrete = 100%, Delivery of steel frame = 80-100%, Fixture and Fittings = 10-50% etc.)

5.2 FORM B – Operatives and Visitors Sign In Sheet

Information Required	Guidance
Induction No.	Ensure this is filled in (if unknown ensure all other information requirements are filled in)
Company Name	Ensure this is filled in
Transport Type	If multiple forms of transport are taken, specify form and distance travelled separately under new data entry
Distance Travelled	Ensure this is filled in (if unknown ensure information relative to 'Travel From' is filled in correctly)

5.3 FORM C – Contractors Resource Forecast

Information Required	Guidance
Date	Ensure this is filled in
Programme Line	Ensure this is filled in and correlates to the Main Programme of Works provided by VINCI (specify 'Programme Revision Letter' as well if available)
Operatives Required	If known specify as much detail as possible (operative names)
Operative Occupation	If known specify as much detail as possible (use generic job names, titles provided)
Plant and Equipment	Ensure this is filled in, provide as much detail as possible (name, type, model no. etc.) Only Specify Plant and Equipment that consumes Energy (red diesel, petrol, electricity etc.) Provide clear indication if specified 'Plant and Equipment Required' is different within each specific 'Programme Activity' (Main Steel Erection….Scissors Lift (A) // Exterior Cladding…Scissors Lift (A) // Roof Cladding….Scissors Lift (B) // in this example the scissors lift used in activity Roof Cladding is different from Steel Erection and Exterior Cladding)

For Advice Contact - **Philip J. Davies** [*contact details removed due to sensitivity*]

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[Form A] PROJECT NAME

Delivery / Collection Sign In Sheet

In order to help us achieve a more accurate Carbon Footprint for our business, please complete the table below to the best of your ability. Thanks in advance for your assistance.

Date	Delivery OR Collection	Delivery Driver Name	Delivery Company Name	Main Delivery Item(s) (if PLANT specify model)	Intended Recipient Name (company OR individual)	Driver Signature	Time In	Time Out	Vehicle Type	Registration No.	Fuel Type	No. Passengers in Vehicle (not driver)	Travel From (city OR postcode)	Distance Travelled (miles)	Onward Travel Distance (miles)	Vehicle Load Capacity (tonne OR m3)	Proportion of Load (% taken-up by delivery item)
04/01/2012	Delivery	T. Holmes	Holmes Deliveries	Ready Mix Concrete	S. Watson	T. Holmes	09:40	12:30	Concrete Mixer	BY13 YSB	Diesel	0	Milton Keynes	130 m	50 m	6 m3	100
04/01/2012	Collection	S. Hall	Lboro Plant Hire	Excavator - Hitachi ZX240	EC Groundworks Ltd.	S. Hall	14:20	14:40	Low Loader	BX11 YZA	Diesel	0	HP5 2ED	45 m	45 m	25 tonne	70
04/01/2012	Delivery	B. Tyson	Quickspeed Ltd.	Insulation Panels	OPO Services	B. Tyson	14:30	15:20	Flatbed Truck	SA09 TTV	Diesel	0	Brighton	170 m	60 m	20 tonne	100
04/01/2012	Delivery	P. Simpson	AC Plant Ltd.	Power Saw - DeWalt DC390N	Agri Construction	P. Simpson	15:10	15:40	Van	AX12 RRA	Petrol	1	Bristol	60 m	60 m	4 m3	10

[Form B] PROJECT NAME

Operatives and Visitors Sign In Sheet

In order to help us achieve a more accurate Carbon Footprint for our business, please complete the table below to the best of your ability. Thanks in advance for your assistance.

Induction No.	Date	Operative Full Name (in capitals)	Signature	Company Name	Time In	Time Out	Transport Type	Registration No.	Fuel Type	No. Passengers in Vehicle (not driver)	Travel From (city OR postcode)	Distance Travelled (miles)
048	04/01/2012	STEPHEN HILL	S. Hill	Taylor Refrigeration Ltd.	07:30	18:00	Car	AA10 QTR	Petrol	0	Reading	20 m
049	04/01/2012	PAUL ANDREWS	P. Andrews	DT Services UK	07:50	17:10	Van	AB12 SJH	Diesel	0	EN9 1FC	110 m

[Form C] PROJECT NAME

Contractor Name ______________________

Date _____ / _____ / _____

Contractors Resource Forecast

In order to help us achieve a more accurate Carbon Footprint for our business, please complete the table below to the best of your ability. Thanks in advance for your assistance.

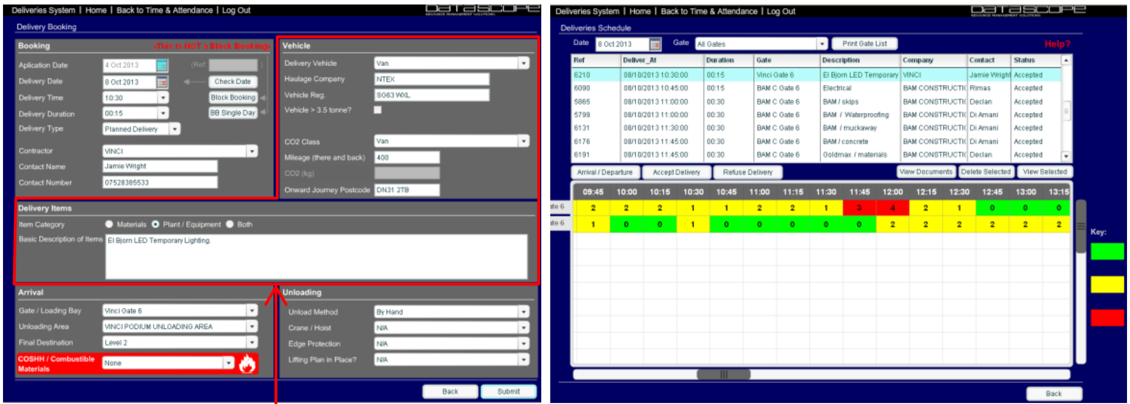
Programme Line	Programme Activity Name	Induction No.	Operatives Required	Operative Occupation	Plant and Equipment Required (consume energy)
46	Main Steel Erection	044	B. Matthews	Steel Erector	Scissors Lift
46	Main Steel Erection	087	A. Fuller	Steelfixer	Power Saw
46	Main Steel Erection	088	T. Day	Plant operator	Crane
NOTE if detailed information about operatives (as above) is not currently available please list information in format below.					
46	Main Steel Erection	/	3 Operatives	Erector; Fixer; Plant Operator	Scissors Lift; Power Saw; Crane

Figure 3.5 Example of the three new sign-in sheets and introduction guide during a live construction project

Furthermore, additional changes were made to the alternative EPI procedure and sign-in sheets to accommodate to a new working environment specific to research cycle five (i.e. Project 3). In terms of the alternative EPI procedure, changes were made to the check-sheets used to capture and verify data to accommodate weekly on-site electrical energy meter readings. In terms of the alternative sign-in sheets, changes were made to the format (i.e. from hard copy to an electronic version) and frequency of data capture with regards to transportation phase energy to adapt to the existing on-line access control system known as Datascope (Datascope, 2014). Essentially, Figure 3.6 displays the changes made by the RE to the on-line access control system to reflect the same data requirements as the developed sign-in sheets (see above). Specifically these changes related to delivery type (materials, plant and equipment, or both), frequency and corresponding coefficient values (i.e. energy and carbon) derived from literature (i.e. DEFRA, 2012).

On-line sign-in sheet (improved)
Used to book deliveries of project resources and capture transportation phase impacts (completed by sub-contractor).

On-line delivery check (maintained)
Used to coordinate on-site logistics and deliveries of project resources (completed by contractor).



Simplified the option for delivery items (materials, plant and equipment, or both), delivery vehicle type and corresponding CO_2 classification.

Figure 3.6 Datascope on-line sign-in sheet and delivery check

3.3.4 Development of Interviews

Interviews were developed to support the exploration of the first research cycle and provide a foundation to support subsequent research cycles. The interviews determined the perspectives of operatives on particular issues relating to the contractor's Environmental Performance Indicator (EPI) procedure introduced previously (see above). The RE identified 10 non-domestic sector operatives at random across each of the three EPI procedure reporting levels (Director, Operations, and Project) for the sample. Due to variation within the geographical location of available construction projects and operative numbers, the sample was exclusively captured from England. Limiting the scope of the sample helped focus time, money and effort expelled by the RE when capturing data; as agreed by the industrial supervisors. In total 17 operatives (6 Director, 6 Operations and 5 Project Level) from the sample agreed to participate within the interviews. The geographical distribution and occupational backgrounds of the interviewees are displayed within Table 3.14. An extensive review of their responses is detailed within paper 1 (Appendix A).

The interviews built upon findings from the review of contractor literature and regression analysis of historic construction project data (see below) to address two fundamental topics: firstly the effectiveness of the EPI procedure towards managing on-site energy consumption data; and secondly in the wider context, how on-site energy management is currently perceived within the contractor. Multiple personal semi-structured interviews provided the RE with flexibility in terms of asking questions (i.e. type and order) and adapting to new views steered by the interviewees. The technique facilitated an interviewer-interviewee interactive discussion surrounding their responsibility, understanding and interaction with the EPI procedure. Also the technique nurtured a degree of consistency and allowed opportunity for further explanation on salient issues through the use of open ended, in-depth questions via probes. Specific question types were used to stimulate positive responses and focus towards particular issues to aid content validity of the captured data (see below). Firstly, knowledge-based questions were used first to determine the interviewee's awareness on issues relating to on-site energy management drivers and current practices. These questions were followed by opinion-based questions which nurtured candid views on issues relating to on-site energy management challenges and opportunities within the contractor and wider industry to help focus the research project towards important unknown issues. A probe sheet which contained pre-formulated responses, was used during the interview and checked when interviewees agreed or disagreed with viewpoint previously noted in literature. In line with good practice recommendations, an interview template was also produced and issued to the interviewees one week prior to the interviews to allow the interviewees a degree of preparation and aid the face validity of the captured data (see below). The template, presented in paper 1 (Appendix A), contained: a brief covering letter, outlining the purpose of interviews; a structure summary, highlighting the content and duration of the interview; as well as details surrounding each question and the purpose of each section. Overall, the outcomes of the interviews influenced the direction of subsequent research cycles; focusing on problems and corresponding practical solutions to help address initial embodied energy consumption.

Table 3.14 Geographical distribution and occupations of the contractor's interview participants

Ref.	Location[a]	Reporting Level[b c d]	Occupation	Gender	Age Group[e]	Experience[f]
1	North West	Project Level	Contracts Manager	Male	45-49 Years	21 Years
2	North West	Project Level	Senior Engineer	Male	30-34 Years	11 Years
3	North West	Project Level	Assistant Engineer	Male	20-24 Years	4 Years
4	North West	Project Level	Senior Engineer	Male	30-34 Years	14 Years
5	South West	Project Level	Administration	Female	20-24 Years	3 Years
6	North East	Operations Level	Design Coordinator	Male	20-24 Years	3 Years
7	Midlands	Operations Level	E&S Consultant	Male	25-29 Years	5 Years
8	Midlands	Operations Level	Administration	Female	40-44 Years	7 Years
9	Midlands	Operations Level	Estimator	Male	30-34 Years	15 Years
10	Midlands	Operations Level	Commercial Manager	Male	30-34 Years	14 Years
11	South East	Operations Level	Design Coordinator	Male	25-29 Years	4 Years

12	North East	Director Level	Director	Male	40-44 Years	21 Years
13	Midlands	Director Level	Director	Male	40-44 Years	21 Years
14	Midlands	Director Level	Director	Male	45-49 Years	23 Years
15	Midlands	Director Level	Regional Director	Male	50+ Years	25 Years
16	Midlands	Director Level	Production Director	Male	45-49 Years	24 Years
17	South East	Director Level	Managing Director	Male	50+ Years	32 Years

[a] Location; geographical location within England.
[b] Director Level operatives; responsible for corporate management and strategy.
[c] Operations Level operatives; responsible for tender management and support services.
[d] Project Level operatives; responsible for on-site operations during construction.
[e] Age Group; 20-24; 25-29; 30-34; 35-39; 40-44; 45-49; 50+ Years.
[f] Experience; total number of years industry experience.

3.3.5 Evaluation of Captured Data

Throughout the research project the RE adopted many methods to evaluate the captured data from the adopted research approaches and techniques. In particular, the RE focused towards apprising data in terms of its reliability and validity. Reliability refers to the consistency and stability of findings over time whereas validity refers to the appropriateness of the measure to assess the construct it intends to measure (Blumberg et al., 2005; Jankowicz, 2005; Burns and Burns, 2008; Fellows and Liu, 2008; Bryman and Bell, 2011; Bryman and Cramer, 2011; Bryman, 2012). Data captured within the current practices employed by the contractor varied significantly throughout the research cycles in terms of content, detail, legibility and terminology. To determine and improve the overall reliability and validity of the captured data the RE frequent undertook random spot-checks of material, transportation and construction phase data. Notably data was checked to ensure specific project resource data (e.g. specific operative, item of equipment) was traceable across current practices (e.g. plant register, sign-in sheets, programme of works) during significant activities on-site such as the start of a new sub-contractor or construction package. The RE commenced these spot-checks during and after an activity. For instance, during an activity such as the delivery of external cladding, the RE undertook several on-site observations and reviewed data being captured by the contractor’s on-site security and traffic marshals in terms of data completeness. The RE produced personal notes and photographs during these instances to provide further evidence regarding the challenges of capturing data within a live construction project. Once the delivery of external cladding was complete the RE compared data captured within the sign-in sheets along with personal notes, photographs and the use of an online search engine (i.e. Google Maps) (Google, 2015) to determine the legitimacy of data relating to vehicle distance travelled and type. Captured data was visually checked by the RE and organised into a consistent format in terms of content, detail, legibility and terminology before being processed and analysed (e.g. Microsoft Excel spreadsheet). The RE initiated meetings with contractor and sub-contractor representatives (i.e. management and operatives) to clarify the findings from the visual inspections and to remediate any discrepancies (e.g. missing data). Issues with regards to data legibility within sign-in sheets for instance were commonly closed-out on-site through interaction with operatives and traffic marshals whereas issues concerning data content within sub-contractor plant registers required more formal discussion and occasionally amended data from the respective sub-contractor management.

The RE also undertook basic calculations in terms of comparing the size and number of material deliveries with the designed volume of material required for a particular construction activity. The RE regularly calculated the size and number of concrete mixer deliveries to site against the designed volume of a particular concrete pour (e.g. floor slab) to ensure that the values comparable. During instances whereby these values were contrasting and no clarification from sub-contractor management was available the RE gave precedence towards designed data values within design drawings and bill of quantities to aid computation as delivery notes were more likely to be misinterpreted and contain errors, as agreed by the industrial supervisors. Throughout data analysis, the RE progressively reprocessed captured data to identify and remediate any significant methodical errors which may have been created by the RE during calculation or sub-contractor operatives during data input. Despite the lengthy process, the recalculation of captured data helped affirm the accuracy and suitability of the data before findings were presented to the industrial supervisors and project team members for review. At this stage the practical use of the data was evaluated and any further amendments in terms of how to capture and analyse different types of data were identified. Overall, the various checks, interactions and calculations adopted by the RE throughout the research cycles intended to enhance the overall confidence within the findings, identify weaknesses within the contractor current practices and determine how these current practices could be further developed throughout the research project in order to limit discrepancies within future captured data.

3.4 Data Analysis

3.4.1 Multiple Regression Analysis

During the first research cycle, a series of multiple linear regression models were developed to examine the usefulness of historic EPI data for predicting on-site energy consumption (i.e. electrical and red diesel usage). The Statistical Package for Social Science (SPSS) 19.0 software was used to evaluate the data captured from the 24 new-build projects (section 4.5.1). The models were created using backward selection methods to distinguish the importance of each project variable (i.e. turnover, site area, direct staff and indirect staff) captured within the EPI data towards predicting the performance of the dependent variables (i.e. on-site electrical and red diesel consumption) across all and specific project types. These models established assorted project variables as significant for different project types. Thus to investigate the relationship between project types, project variables and dependent variables across the sample, an overall model combining all data (including multiple interaction terms) was developed for each dependent variable. This overall model was created to determine whether it could successfully fit the sampled data and potentially generalise to other samples. Although, the corresponding regression diagnostics revealed non-linearity and non-constant variance across the modelled data, hence log transformations were used to reduce the subsequent prediction errors. Scatter plots were used to visualise the impact of these transformations and highlight outliers within the sampled data, as illustrated in Figure 3.7.

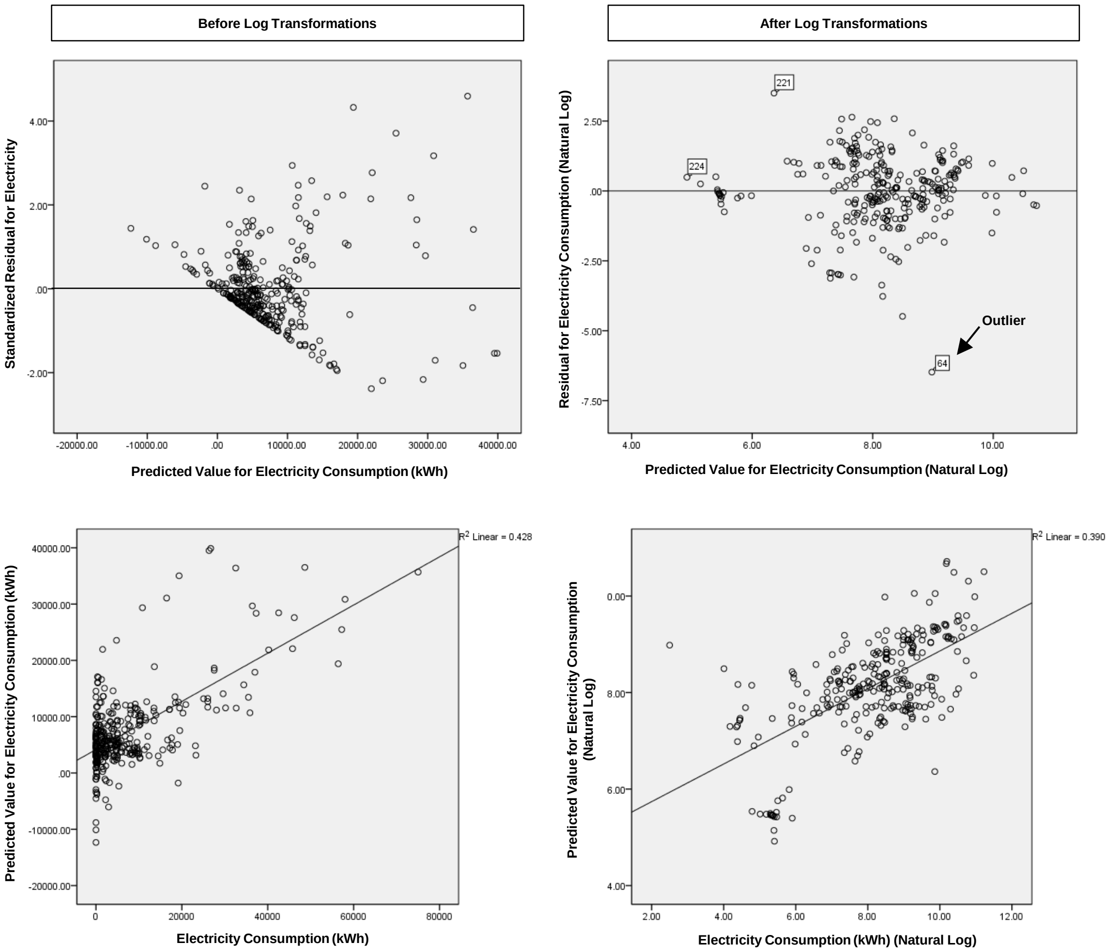


Figure 3.7 Example of scatter plots derived from the multiple regression analysis

Therefore, two final models were developed; one model considered the influence of project type as opposed to the other. Each model consisted of a different set of modelled equations intended to predict the performance (i.e. natural logarithmic values) of each dependent variable. Table 3.15 displays the composition of the modelled equations for electrical and red diesel consumption prediction derived from the two models; ‘All Projects’ (AP) and ‘Project Type’ (PT) specific.

Table 3.15 All modelled equations for electrical and red diesel consumption prediction

Equation Type[a]	Electricity Modelled Equation (kWh)[b]	Red Diesel Modelled Equation (litres)[b]
(AP) All Projects[c]	= [7.202] + [-2.006E-7(T)] + [0.123(DS)]	= [6.364] + [1.591E-5(SA)] + [0.079(DS)]
(PT) College[d]	= [5.112] + [-1.725E-6(T)] + [0.441(DS)] + [7.894E-3(IS)]	= [2.515] + [1.183E-4(SA)] + [0.004(IS)]
(PT) Hospital[d]	= [7.939] + [1.925E-7(T)] + [0.106(DS)] + [-0.006(IS)]	= [7.150] + [-1.922E-5(SA)] + [0.004(IS)]
(PT) School[d]	= [7.331] + [3.613E-7(T)] + [0.136(DS)] + [-0.010(IS)]	= [6.158] + [4.097E-5(SA)] + [0.004(IS)]
(PT) University[d]	= [2.034] + [-1.773E-8(T)] + [0.308(DS)] + [0.008(IS)]	= [6.194] + [1.184E-4(SA)] + [0.004(IS)]

[a] Equation Type; All Projects (AP); Project Type (PT) specific.
[b] Project variables; T, Turnover (£); SA, Site Area (m^2); DS, Direct Staff (No.); IS, Indirect Staff (No.).
[c] Electricity R^2 = 0.138 (Adjusted R^2 = 0.132); Red Diesel R^2 = 0.148 (Adjusted R^2 = 0.136).
[d] Electricity R^2 = 0.385 (Adjusted R^2 = 0.351); Red Diesel R^2 = 0.310 (Adjusted R^2 = 0.277).

3.4.2 Spreadsheet Analysis

All data captured across the five research cycles was organised and analysed via many Microsoft Excel spreadsheets. These spreadsheets were used to summarise and interpret data captured from a review of literature (industry or contractor) and on-site current practices via the production of frequency counts, distributions, percentages and pictorial representations. The use of a simple data management approach ensured that outputs derived from each research cycle (e.g. alternative on-site current practice) were compatible, readily integrated into the workings of the contractor and were in a recognisable format that could be understood by subjects (i.e. sub-contractor management, operatives) with no additional training required. Table 3.16 displays an example of data organised from a review of industry literature that helped identify what project indicators were important when capturing and assessing initial embodied energy consumption (section 4.6.1).

Table 3.16 Example of data captured from industry literature to support exploration of on-site current practices (after Davies et al., 2014, paper 3)

	Project Life Cycle Phase[1]	MAT	TRAN						TRAN						TRAN						CON						
	Project Resource	Materials	Materials						Plant and Equipment						Operatives						Mat, Plant and Equipment, and Ops						
	Embodied Energy Indicators and Units[2]	a	b	c	d	e	f	g	b	c	d	e	f	g	b	c	d	e	f	g	c	c	c	h	d	e	i
Ref.	**Reference**	Characteristics	Distance Travelled	Vehicle Used	Vehicle Fuel	Vehicle Fuel Type	Vehicle Load Capacity	Proportion of Load	Distance Travelled	Vehicle Used	Vehicle Fuel	Vehicle Fuel Type	Vehicle Load Capacity	Proportion of Load	Distance Travelled	Vehicle Used	Vehicle Fuel	Vehicle Fuel Type	Vehicle Load Capacity	Proportion of Load	Material Needed	Operatives Needed	Plant Needed	Plant Duration of Use	Plant Fuel Type	Plant Fuel Consumed	Plant Power Rating
1	Adalberth (1997)	1	1	1																			1				
2	Blengini and Di Carlo (2010)	1	1	1																			1				
3	Bribian et al. (2011)	1	1	1			1																				
4	Chang et al. (2012)	1	1	1	1	1	1																1		1	1	1
5	Chen et al. (2001)	1	1	1																							
6	Cole (1999)	1	1	1	1	1	1	1	1	1	1	1			1	1	1	1				1	1	1	1	1	
7	Cole and Kernan (1996)	1																									
8	Emmanuel (2004)	1																									
9	Fay et al. (2000)	1																									
10	Fieldson and Rai (2009)	1																					1		1		
11	Goggins et al. (2010)	1	1	1	1	1	1	1																			
12	Gustavsson et al. (2010)	1																							1		
13	Halcrow Yolles (2010)	1																									
14	Huberman and Pearlmutter (2008)	1	1	1	1																						
15	Kellenberger and Althaus (2009)	1	1	1			1	1															1				
16	Kofoworola and Gheewala (2009)	1	1	1	1				1			1											1		1	1	
17	Leckner and Zmeureanu (2011)	1	1	1			1																				
18	Li et al. (2010)	1	1																				1	1	1	1	
19	Monahan and Powell (2011)	1	1												1										1	1	
20	Pearlmutter et al. (2007)	1	1	1	1	1																					
21	Rai et al. (2011)	1																									
22	Scheuer at al. (2003)	1	1	1																			1	1	1	1	
23	Smith et al. (1997)	1	1																								
24	Sodagar et al. (2008)	1	1	1	1	1			1	1					1	1						1	1			1	
25	Venkatarama Reddy and Jagadish (2003)	1	1		1																						
	Frequency Count	25	18	14	8	5	6	3	3	2	1	2	0	0	3	2	1	1	0	0	0	2	10	3	8	7	1
	Percentage	100	72	56	32	20	24	12	12	8	4	8	0	0	12	8	4	4	0	0	0	8	40	12	32	28	4

[1] Project Life Cycle Phase: M, Material Phase.

[2] Embodied Energy Indicator Units: a (type, no., m^2 m^3, tonne); b (miles, km); c (type, no.); d (petrol, diesel, etc.); e (litres, kWh); f (tonne, m^3); g (%); h (hrs, days); i (v, a, watts).

3.4.3 Content Analysis

Content analysis was used to evaluate the qualitative data captured from the interviews undertaken within the first research cycle. Firstly, with permission granted by the interviewees, all interviews were recorded via a tape recorder to generate full transcripts. Once all interviews were complete, transcripts were reviewed by the RE and data (in the form of text) was inputted into a Microsoft Excel spreadsheet to be organised. A deductive approach was used to analyse the data via the use of a matrix table and frequency counts to determine whether interviewees agreed or disagreed with the preselected themes derived from the RE's insight and supporting research approaches (i.e. critical review of contractor literature and regression analysis) (Fink, 2003; Bryman, 2004). Table 3.17 displays an example of a frequency count used to summarise the most common interviewee responses per question topic from each EPI reporting level (section 4.5.1).

Table 3.17 Example of frequency count summary of interviewee responses per question topic (sample)

Ref.[a]	S[b]	Question Topic	Common Interviewee Responses[c]	Totals[d]			
				P	O	D	Tot
35	**Opportunities**	Examples of current key opportunities	EPI reflects commitment to reduce environmental impact	0	0	1	1
36			Capture additional project variables to improve data quality	2	3	3	8
37			Capture additional project variables to improve understanding of energy use on-site	3	2	5	10
38			Benchmark performance to increase best practice etc.	1	5	5	11
39			Benchmark performance to enable comparison and ranking	0	1	1	2
40			Using red diesel generators on-site is common	5	6	6	17
41			Earlier electrical-grid connection can improve accuracy of data	2	5	5	12
42			Earlier electrical-grid connection can reduce red diesel	2	5	4	11
43			Improved efficient behaviour due to new electricity tariff	0	4	1	5
44			Improved ability to forecast earlier electrical-grid connection due to new electricity tariff	0	4	1	5
45			Increased feedback to improve on-site energy management awareness and approach	4	4	3	11
			Total number of responses per Reporting Level	**85**	**113**	**118**	
			Total number of operatives per Reporting Level	**5**	**6**	**6**	
			Total number of responses from all questions				**316**

[a] Ref.: Response reference from interviewees keyed to Appendix A.
[b] S, Section of the interview.
[c] Common Interviewee Reponses: EPI, Environmental Performance Indicator Procedure; H&S, Health and Safety; COINS, Construction Industry Solutions commercial web based database.
[d] Totals: P, Number of Project Level responses; O, Number of Operations Level responses; D, Number of Director Level responses; Tot, Total number of responses; Highlighted values resemble top 10% (5 or 6 in number) of responses per reporting level.

3.4.4 Uncertainty in Analysis

Three components formed the basis of all values and results obtained within the research, as illustrated below within equation 1 (Fink, 2003; Blumberg et al., 2005; Jankowicz, 2005; Field, 2009; Bryman and Bell, 2011; Bryman, 2012):

$$\textit{Measured Value (captured)} = \textit{True Value (desired)} \pm \textit{Error (uncertainty)} \qquad (1)$$

Variability within the measured values derived from either actual differences between the ability of individuals or equipment to undertake a task, or error in measurement, in the form of random fluctuation or systematic error. Despite intentions to conclude accurate reliable results (i.e. true values), the RE acknowledged the presence of measurement error within the captured and analysed data, which caused a degree of uncertainty within the findings.

Random fluctuation error relates to measurement as influenced by irrelevant or chance factors such as variation in individual health, mood and motivation or temporary changes to weather and working conditions. Due to the nature of the construction work in terms of daily changes in environment and workforce, these errors were expected and thus identified during observational techniques and data capture within the explored construction projects. Practical examples of instances observed by the RE which simulated random fluctuation error were as follows: operatives using more materials than required during an on-site activity; operatives making a mistake which required rework; operatives using an alternative mode of transport or route to work; operatives not signing in or out when attending or leaving site; operatives spilling fuel on-site; operatives having to repair broken down plant or equipment; operatives receiving late delivery of construction materials; operatives experiencing electrical power outages; and operatives having to adapt to late changes in construction design. Though the true number and significance of these errors was not fully investigated or clearly distinguished within the captured data. This was due to an unknown number of causes that would have been impractical to determine, given the RE’s resources and timescale of the research project; a decision supported by the industrial supervisors.

Systematic error relates to measurement which has been subjected to an unwanted variable that has influenced values in one direction. This form of error was present within the electrical energy meters used to provide primary energy consumption data (section 4.6.3) or secondary energy consumption data (4.5.1). In addition, this form of error was present within the calculation of total initial embodied energy consumption for each live construction project as only a sample of construction packages, activities and sub-contractors were investigated (see above). Hence overall measured values (i.e. energy consumption) for the total construction project or individual life cycle phases (i.e. material, transportation, construction) were expected to be an underestimate of the true values. Table 3.18 displays how uncertainty caused by systematic error was considered when calculating the material phase energy within the explored construction projects. The evidence highlights the relationship between the measured values, potential true values (i.e. lower and upper bound limits), and associated degree of uncertainty (e.g. ±10%). Material quantities were derived from the contractor's on-site current practices (e.g. BoQ, design drawings) and converted into material mass (kg) for calculation. Through professional judgement in accordance with the industrial supervisors, the RE estimated a degree of uncertainty of ±10% surrounding the measured material quantities. This value represented potential discrepancies within the measured values caused by material wastage, damage, variation and over-ordering; all of which were deemed likely to occur during on-site construction and may not be evident within the captured data within the on-site current practices. The material rates (i.e. embodied energy coefficients) were derived from the ICE material database which included a varied degree of uncertainty for each material (e.g. ±8% for copper, ±12% for iron, ±40% for rockwool) as some materials were only sourced from a few records which supported the database (e.g. the material rate for steel was sourced from only two records). Therefore, the RE used a value of ±30% to reflect the overall degree of uncertainty across all material rates as this was the most common value within the database and, in particular, was used to reflect the degree of uncertainty within steel and concrete; materials which are commonly used within construction projects. Hence, the potential measurement error when calculating the material phase energy from the sources identified through combining the uncertainties in quadrature was approximately ±32% (Harvard University, 2015). This value was an approximate average value derived from the difference between the lower and upper bound limits which represented the potential lowest and highest calculated values for material quantity and rates combined respectively. For example, in terms of the precast concrete material used within the groundworks construction package (second row in Table 3.18), the lowest material quantity and rate was 10% and 30% less than the measured values respectively (i.e. 104,000 kg and 0.52 MJ/kg), resulting in a total material phase energy consumption of 36,800 MJ (or $3.68x10^4$); in contrast to the measured value of 54,100 MJ (or $5.41x10^4$).

Table 3.18 Example of uncertainty within material phase energy calculations from research cycle 4 (Project 2)

Construction Package	Material Type	Material Quantity (kg)[a] [±10%][c]		Material Rate (MJ/kg)[a] [±30%][c]		Total Material Phase Energy (MJ)[b] [±32%][d]	Total Lower Bound Limit (MJ)[c] [-32%][e]	Total Upper Bound Limit (MJ)[c] [+32%][e]
Earthworks	Aggregate	8.47E+07	x	0.05	=	4.24E+06	2.88E+06	5.59E+06
Groundworks	Precast C’	1.04E+05	x	0.52	=	5.41E+04	3.68E+04	7.14E+04
Groundworks	HDPE	2.88E+02	x	84.4	=	2.43E+04	1.65E+04	3.20E+04
Groundworks	Clay	2.07E+04	x	7.90	=	1.64E+05	1.11E+05	2.16E+05
Groundworks	Precast C’	4.26E+04	x	1.26	=	5.37E+04	3.65E+04	7.09E+04
Groundworks	Concrete	5.75E+06	x	1.79	=	1.03E+07	7.01E+06	1.36E+07
Frame	Steel	1.28E+06	x	28.7	=	3.66E+07	2.49E+07	4.83E+07
External Walls	Rigid Foam	2.51E+05	x	101.5	=	2.55E+07	1.73E+07	3.36E+07
Ground Floor	Concrete	3.14E+07	x	7.75	=	2.43E+08	1.65E+08	3.21E+08
Upper Floor	Concrete	3.97E+05	x	0.97	=	3.85E+05	2.62E+05	5.08E+05
External Slab	Concrete	3.63E+07	x	2.05	=	7.45E+07	5.07E+07	9.84E+07
Retaining Walls	Precast C’	1.12E+06	x	1.46	=	1.63E+06	1.11E+06	2.15E+06
Electrical	Steel	1.81E+05	x	36.0	=	6.51E+06	4.43E+06	8.60E+06
Mechanical	Steel	4.23E+04	x	34.4	=	1.46E+06	9.90E+05	1.92E+06
Mechanical	Copper	1.98E+03	x	40.0	=	7.91E+04	5.38E+04	1.04E+05
Syphonic D’	Iron	2.00E+05	x	25.0	=	5.01E+06	3.41E+06	6.61E+06
Dock Levellers	Steel	1.05E+06	x	21.5	=	2.27E+07	1.54E+07	2.99E+07
Internal Walls	Rockwool	1.98E+04	x	16.8	=	3.32E+05	2.26E+05	4.39E+05
Totals						4.33E+08	2.94E+08	5.71E+08

[a] Measured values: represent the material quantities and rates derived from on-site current practices and the ICE material database.
[b] Total material phase energy: derived from multiplying the material quantity with the material rate.
[c] Error: represent the potential measurement error based upon the measured values defined as a percentage (i.e. relative uncertainty).
[d] Error: combining the material quantity and rate uncertainties in quadrature (i.e. $(\sqrt{\pm10\%^2 + \pm30\%^2}) = \pm32\%$).
[e] Limits per material: sum of all lower bound limits (i.e. -32%); sum of all upper bound limits (i.e. +32%).

The RE used the same value ±32% to reflect the total degree of uncertainty across the quantities and rates used to analyse transportation and construction phase data. However, the RE assumed uncertainty surrounding the quantities for transportation and construction phase data would be more significant (e.g. ±30%) than for the material phase data previsouly as these values would be more subject to increased random fluctuation errors caused by operatives (see above). The Defra Guide used to provide the rates for both transportation and construction phase data did not specify an uncertainty value within the dataset, hence the RE used professional judgement to assume there would likely be some degree of uncertainty surrounding the rates (e.g. ±10%).

Table 3.19 summaries the relationship between the measured values, errors and corresponding sources required to calculate total initial embodied energy consumption across individual life cycle phases for each explored construction package, activity and sub-contractor. As highlighted previously, the percentage errors reflect the overall degree of uncertainty (in this case relative uncertainty) within the measured values caused by numerous random fluctuation and systematic errors. The size of the error influenced the overall precision and accuracy of the measured values within individual life cycle phases and total initial embodied energy consumption for the explored construction projects. Overall, the RE acknowledged the presence and size of these errors would impact the findings derived from the explored construction projects in terms of highlighting the most significant construction packages, activities, sub-contractors or even individual life cycle phases. Acknowledging the degree of uncertainty within the results from each research cycle would help improve the overall transparency of the findings and help draw attention towards overcoming these measurement errors within subsequent research cycles and future research.

Table 3.19 Series of key measured variables and sources of error

Life Cycle Phase Data	Measured Values	Error (±%)	Source (sample)
Material phase data	Material quantities (kg) Material rates (MJ/kg)	±10% ±30%	BoQ, design drawings, on-site operatives ICE material database
Transportation phase data	Transport quantities (unit) Transportation rates (kWh/unit)	±30% ±10%	Sign-in sheets, on-site operatives DEFRA guide
Construction phase data	Construction plant quantities (unit) Construction rates (kWh/unit)	±30% ±10%	Sign-in sheets, plant register, on-site operatives DEFRA guide

4 RESEARCH UNDERTAKEN

This chapter describes the actions undertaken in order to fulfil the aims and objectives of the research. The chapter highlights the sequence of events which led to the production of four papers, all of which are presented within Appendix A to Appendix D.

4.1 Preliminary Studies

In line with the requirements of the EngD the RE completed post graduate modules at Loughborough University. Compulsory modules provided the RE with essential knowledge and experience in evaluating research methods, enhancing personal management and professional development, producing small-scale research projects, and exploring the industrial sponsor's organisational culture. Two additional optional modules were taken (Renewable Energy and Low Carbon Technology plus Building Control and Commissioning) which were of personal interest to the RE and resembled some relevance towards energy consumption of buildings (i.e. operational phase energy). In addition the RE participated in many academic and industry-based training courses. These contributed to the RE's professional development, academic knowledge, and industry competency. A summary of the training courses undertaken are presented in Appendix F.

As highlighted previously (section 1.2) the research project evolved from a single client perspective to a wider client perspective which helped focus attention towards building delivery rather than building operation. During the transition, a preliminary study in the form of a critical review of industry literature was undertaken which considered the basic characteristics of operational energy consumption. The RE deemed it important to take this opportunity to acknowledge a broad perspective of a life cycle approach towards buildings to determine whether the basic characteristics of operational energy consumption could be applicable to and influence how initial embodied consumption could be addressed. The key findings of the preliminary study are summarised in Appendix F

4.2 Research Progression

To manage the requirements of the EngD two programmes were created and updated throughout the research project to reflect progress and any changes to adopted research methods. The programmes were as follows:

1. The EngD Work Programme demonstrates all of the outputs needed to fulfil the requirements of the EngD (Appendix G).
2. The EngD Research Development Programme displays the relationship between the research objectives, adopted research methods, and papers (Figure 4.1). The duration of each construction project which the RE was actively involved in is also highlighted.

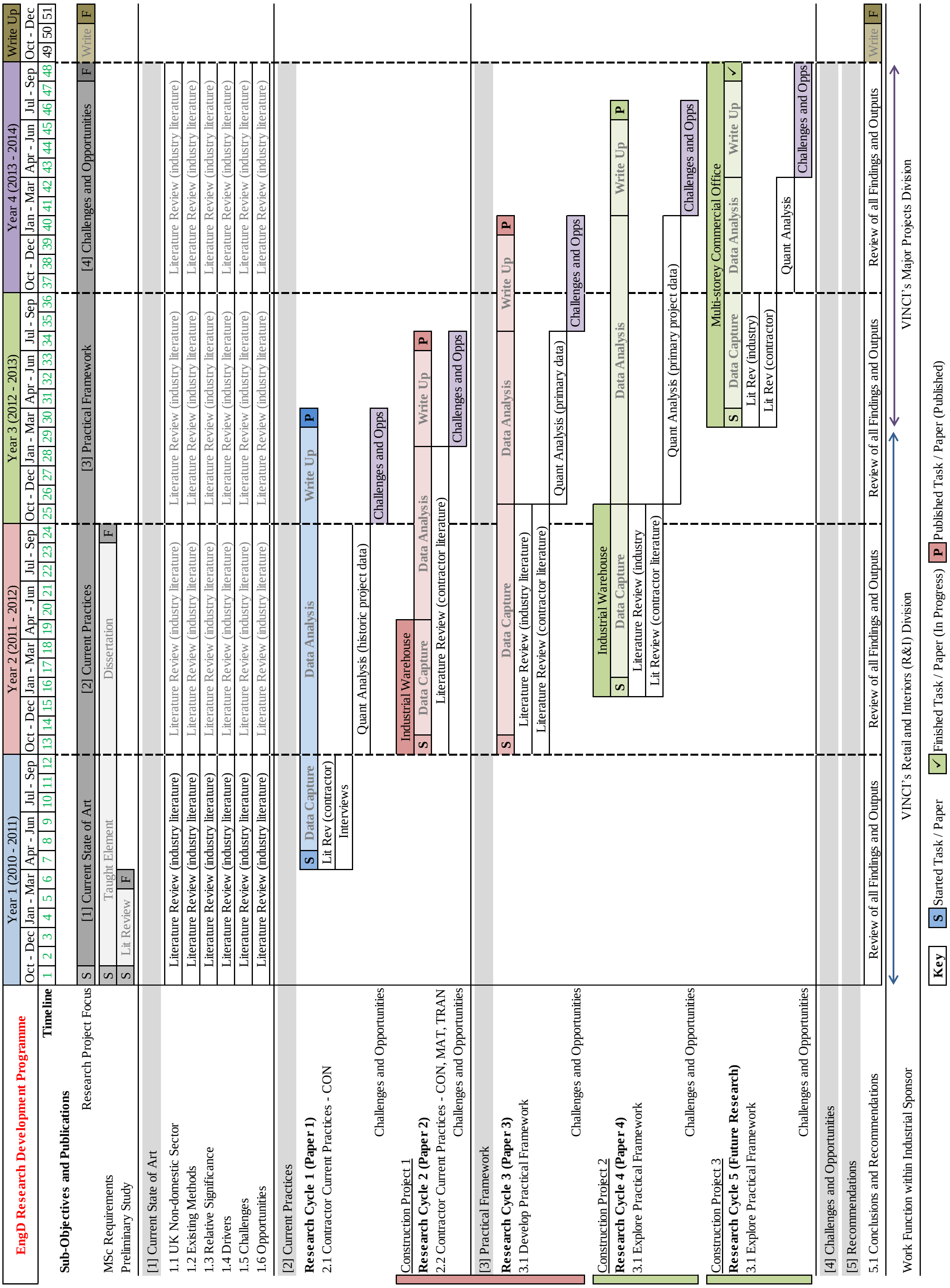


Figure 4.1 EngD Research Development Programme

4.3 Research Overview

The research contained five overarching objectives (section 1.4) whereby an overview of the research leading questions and outcomes per objective is displayed within Table 4.1. A review of the research structure, cycles, papers and lessons learned is presented.

Table 4.1 Overview of the research leading questions and practical outcomes per overarching objective

Overarching Objective		Leading Questions	Outcome	Reference
1	Current State of Art	What does the industry know?	Literature Review	Section 4.4
2	Current Practices	What does the contractor know?	Paper 1, Paper 2	Section 4.5 (Appendix A and Appendix B)
3	Practical Framework	What can the contractor do?	Paper 3, Paper 4	Section 4.6 (Appendix C and Appendix D)
4	Challenges and Opportunities	How can the contractor improve the situation?	All Papers	Section 4.7
5	Recommendations	What do the findings mean to the industry?	All Papers	Section 6.6

4.3.1 Research Structure

The chapter demonstrates the research undertaken in line with the overarching objectives and sub-objectives. Each section is structured as per Figure 4.2 and references specific research cycles and papers. In particular, each research cycle is discussed in terms of diagnosing and action planning, action taking, evaluating and specified learning.

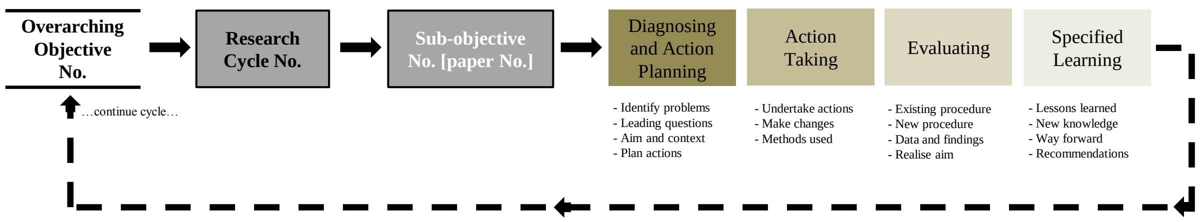


Figure 4.2 Structure of the remaining sections within chapter four

4.3.2 Research Cycles

Overarching objectives 2 and 3 were undertaken through the creation of multiple research cycles which concluded four research papers. Basic characteristics of these research cycles and their relationship with the objectives are illustrated in Table 4.2.

Table 4.2 Basic characteristics of each research cycle

Details	**Case Study Characteristics**				
	Research Cycle 1	**Research Cycle 2**	**Research Cycle 3**	**Research Cycle 4**	**Research Cycle 5**
Paper Referred Name	Paper 1	Paper 2	Paper 3	Paper 4	Future Research[b]
Paper Type	Journal Paper	Conference Paper	Journal Paper	Journal Paper	Journal Paper
Paper Progress (Start-Finish)	Year 1 – Year 3	Year 2 – Year 3	Year 2 – Year 4	Year 2 – Year 4	Year 3 – on-going
Current Status	Published	Published	Published	Published	[In process]
Aim (Key Words)	On-site Energy Management	Addressing Embodied Energy	Capturing and Assessing	Improve Initial Embodied Energy Efficiency	Challenges and Opportunities
Life Cycle Phase Focus	Construction Phase	Material, Transportation and Construction Phases	Material, Transportation and Construction Phases	Material, Transportation and Construction Phases	Material, Transportation and Construction Phases
Overarching Objective No.	[2] Current Practices	[2] Current Practices	[3] Practical Framework	[3] Practical Framework	[3] Practical Framework
Sub-Objective No.	2.1 Contractor Current Practice - CON	2.2 Contractor Current Practice – MAT, TRAN, CON	3.1 Develop Practical Framework	3.2 Explore Practical Framework	3.2 Explore Practical Framework
Data Source (Key Words)	Historic Data (EPI)[a]	Construction Project 1	Construction Project 1	Construction Project 2	Construction Project 3
Construction Project Type	Hospitals, Schools, Colleges, Universities	Industrial Warehouse (Temperature Controlled)	Industrial Warehouse (Temperature Controlled)	Industrial Warehouse (Ambient)	Multi-Storey Commercial Office

[a] Historic Data: EPI, Environmental Performance Indicator Procedure.
[b] Future Research: See Appendix H.

4.3.3 Research Papers

The following tables (Table 4.3 to Table 4.6) display the headline information of each research paper referenced within the next section. In particular, the tables summarise the aim, method and key results from each paper. Appendix H presents the basis of future research papers, currently in process, that have directly stemmed from the development of the research project and the RE's active involvement within the industrial sponsor.

Table 4.3 Research paper 1 headlines (after Davies et al., 2013a)

Content	Headline Information
Paper Referred Name	**Paper 1**
Paper Full Reference	Davies, P.J., Emmitt, S., Firth, S.K. (2013a) On-site energy management challenges and opportunities: a contractor's perspective. *Building Research & Information*, 41(4), 450-468.
Aim	The aim of the research paper was to investigate the key challenges and opportunities for delivering on-site energy management within UK non-domestic projects from a contractor's perspective.
Context and Justification	The contractor is principally responsible for the energy use during the construction phase, hence: - What type and level of data does the contractor already capture regarding construction phase energy consumption? - How useful is historic data in predicting future construction phase energy consumption? - How is construction phase energy consumption currently perceived by contractor operatives?
Method	A case study approach was adopted consisting of a desk study, quantitative analysis and interviews, hence: - The desk study examined the contractor's current on-site energy management procedure (i.e. Environmental Performance Indicators, EPI); - The quantitative analysis reviewed historic EPI data from UK non-domestic construction projects and developed models to predict on-site energy use relative to a series of variables; - The interviews explored the contractor operatives' responsibilities, understanding and interaction with the EPI procedure.
Results and Conclusions	The key research results and conclusions were as follows: - The 'Project Type' (PT) specific model was more accurate at predicting energy consumption than the 'All Projects' (AP) model; - The type and level of data captured within the EPI procedure alone does not accurately reflect how or why energy is consumed during project development; - Lack of detailed data authentication was deemed as a significant challenge; - Capture additional project variables to facilitate future benchmarking was deemed as a significant opportunity; - Limited knowledge surrounding the outcome which could occur from targeting reduced construction phase energy consumption.
Recommendation	The key research recommendation was as follows: - To capture additional project variables to increase the granularity of data and facilitate future benchmarking of on-site energy consumption.

Table 4.4 Research paper 2 headlines (after Davies et al., 2013b)

Content	Headline Information
Paper Referred Name	**Paper 2**
Paper Full Reference	Davies, P.J., Emmitt, S., Firth, S.K., Kerr, D. (2013b) Addressing embodied energy from a contractor's perspective. *Sustainable Building Conference SB13*, 3-5 July, Coventry.
Aim	The aim of the research paper was to investigate the key challenges and opportunities for addressing embodied energy levels within UK non-domestic projects from a contractor's perspective.
Context and Justification	The contractor has a vested interest in initial embodied energy (primarily transportation and construction phase energy) due to their significant involvement in project procurement, pre-construction and on-site construction activities, hence: - What is the relative significance of individual project life cycle phases (material, transportation, construction) for different project types?

	- What current practices does the contractor employ during the construction phase of a project which could help assess initial embodied energy consumption?
Method	A case study approach was adopted consisting of two desk studies, hence: - The first desk study reviewed existing life cycle assessment (LCA) studies to determine the relative significance of individual project life cycle phases; - The second desk study appraised a series of contractor current practices post construction to determine their potential to support an initial embodied energy assessment.
Results and Conclusions	The key research results and conclusions were as follows: - Limited LCA studies focused towards UK non-domestic construction projects; - Limited LCA studies illustrated impacts relative to individual project life cycle phases; - Material phase impacts were deemed significant in comparison to transportation and construction phase impacts; - Wide range of values used to portray the significance of initial embodied energy relative to total project life cycle energy across assorted project types; - Improved consistency within LCA studies is needed to better understand the relative significance of individual project life cycle phases; - Limited potential within existing LCA studies in supporting the development of benchmarks and targets for future energy reduction; - Difficult at present for contractor to evaluate the initial embodied impact of different aspects of a building based upon current practices; - Attempts to reduce the initial embodied impact of a particular building aspect may lead to changes in the impact of different project life cycle phases.
Recommendation	The key research recommendation was as follows: - To develop a LCA approach (i.e. framework) that highlights the relative significance of individual life cycle phases for a UK non-domestic construction project.

Table 4.5 Research paper 3 headlines (after Davies et al., 2014)

Content	Headline Information
Paper Referred Name	**Paper 3**
Paper Full Reference	Davies, P.J., Emmitt, S., Firth, S.K. (2014) Challenges for capturing and assessing initial embodied energy: a contractor's perspective. *Construction Management and Economics*, 32(3), 290-308.
Aim	The aim of the research paper was to investigate the practical challenges for capturing and assessing initial embodied energy levels within the UK non-domestic from a contractor's perspective.
Context and Justification	Existing life cycle assessment (LCA) studies have not explored a practical approach for the assessment of initial embodied energy levels which could be readily adopted by project stakeholders, hence: - What project life cycle phases and associated embodied energy indicators are typically considered within LCA studies? - What type and level of data does the contractor already capture associated with the energy consumptionof individual project life cycle phases? - What is the relative significance of individual project life cycle phases (material, transportation, construction) for a specific UK non-domestic construction project?
Method	A case study approach was adopted consisting of a desk study and quantitative analysis, hence: - The desk study nurtured the development of a practical framework intended to address the inherent weaknesses common to LCA studies; - The quantitative analysis assessed data captured by the framework from a live UK non-domestic construction project.
Results and Conclusions	The key research results and conclusions were as follows: - The framework has potential to support future benchmarking and target setting; - Contractor has a unique opportunity to capture primary data throughout the transportation and construction phases; - Material phase impacts were deemed significant in comparison to transportation and construction phase impacts;

	- Ground and upper floor, external slab and frame were the most significant construction packages; - Findings demonstrated no direct relationship between construction packages, activities and sub-contractors; - Majority of transportation impacts were not assessed because of inadequacies of the contractor's sign-in sheets; - Capturing additional indicators (e.g. type and number of plant and equipment per construction activity) can help improve granularity of data; - Attempts to reduce material phase impacts may influence the type and number of project resources required.
Recommendation	The key research recommendation was as follows: - To develop a revised framework that highlights the significance of construction packages, activities and sub-contractors in terms of individual life cycle phases for a UK non-domestic construction project.

Table 4.6 Research paper 4 headlines (after Davies et al., 2015)

Content	Headline Information
Paper Referred Name	**Paper 4**
Paper Full Reference	Davies, P.J., Emmitt, S., Firth, S.K. (2015) Delivering improved initial embodied energy efficiency during construction. *Sustainable Cities and Society*, 14, 267-279.
Aim	The aim of the research paper was to investigate the practical challenges and opportunities for delivering improved initial embodied energy levels within the UK non-domestic from a contractor's perspective.
Context and Justification	Understanding the significance of individual project life cycle phases and the relationship between them is essential for project stakeholders to reduce overall project life cycle energy, hence: - What modifications can be made to the framework and contractor's current practices to capture improved data? - Is their similarities between the relative significance of individual project life cycle phases (material, transportation, construction) for comparable project types?
Method	A case study approach was adopted consisting of a desk study and quantitative analysis, hence: - The desk study nurtured the development of a revised framework, which primarily included three new sign-in sheets, intended to address the inherent weaknesses of the initial framework; - The quantitative analysis assessed data captured by the revised framework from a live UK non-domestic construction project.
Results and Conclusions	The key research results and conclusions were as follows: - Material phase impacts were deemed significant in comparison to transportation and construction phase impacts; - Ground and upper floor, external slab and frame were the most significant construction packages; - Further standardisation of units for environmental measurement is required to improve correlation of data; - Difficult to accurately assess impact for each construction activity as sub-contractor data varied in terms of content, detail and terminology; - Significant impacts were derived from outside the building footprint area (e.g. external slab for servicing vehicle movements); - Material quantities, characteristics and performance criteria need to be considered when targeting reduced material phase impact; - Important to source high embodied impact materials locally (e.g. concrete) and reduce reliance upon red diesel fuelled plant-intensive construction activities; - Attempts to reduce material phase impacts may influence transportation, construction and operational phase impacts; - The initial embodied impact was found greater than the operational impact at the end of the building's life (i.e. actual embodied energy data compared against designed operational data).
Recommendation	The key research recommendation was as follows: - To investigate the relationship between individual project life cycle phases and the impact

	operational energy reduction has on initial embodied energy consumption.

4.3.4 Research Lessons Learned

Multiple lessons learned were identified during research development. Table 4.7 summarises the lessons learned derived from each research cycle and illustrates how attempts were made to build upon and adopt each lessons learned within subsequent research methods.

Table 4.7 Summary of lessons learned from research undertaken

RC No[a]	Adopted Methods[b]		Lessons Leaned	Link
Pre-Cycles	Main Industry Literature Review		- Improve comprehension of methods and assumptions made by practitioners within previous LCA studies;	**D,G**
			- Enhance awareness of the relative significance of individual life cycle phases;	**A,D**
			- Develop further appreciation of the opportunities and challenges for different project stakeholders to consider initial embodied energy consumption.	**L,O**
Research Cycle 1	Industry and Contractor Literature Review	**A**	- Enhance development of data capture and validation techniques during construction;	**H,K**
	Quantitative Analysis	**B**	- Increase awareness of alternative project variables and indicators across different project life cycle phases which influence energy consumption;	**D,G**
	Interviews	**C**	- Improve consideration towards data benchmarking and target setting to drive reduced energy consumption during construction.	**Rec**
Research Cycle 2	Industry Literature Review	**D**	- Develop a consistent approach towards the capture of project data across individual initial embodied energy phases (i.e. material, transportation and construction);	**G,H**
	Contractor Literature Review	**E**	- Increase awareness of data associations between construction packages, construction activities and sub-contractors;	**I,L**
		F	- Improve consideration of the relationship between individual life cycle phases.	**G,J**
Research Cycle 3	Industry Literature Review	**G**	- Increase awareness of the relationship between individual project life cycle phases (including operational energy);	**L**
	Contractor Literature Review	**H**	- Enhance current practices to capture detailed project data across construction packages, construction activities and sub-contractors relative to individual initial embodied energy phases (i.e. material, transportation and construction);	**J,K**
	Quantitative Analysis	**I**	- Improve consideration towards the validation of captured project data.	**K**
Research Cycle 4	Industry Literature Review	**J**	- Enhance current practices to capture detailed construction package and project specific data for future benchmarking;	**Rec**
	Contractor Literature Review	**K**	- Increase awareness of the practical challenges which inhibit data capture during a live construction project;	**N,O**
	Quantitative Analysis	**L**	- Improve consideration towards the practical opportunities which support initial embodied energy reduction during a live construction project.	**N,O**
Research Cycle 5	Contractor Literature Review	**M**	- Develop an approach towards accurately accounting for construction phase energy per sub-contractor during the use of mixed energy sources;	**Rec**
	Quantitative Analysis	**N**	- Improve awareness of project stakeholders involved and decisions made during pre-construction to address initial embodied energy consumption;	**Rec**
		O	- Increase comprehension of how initial embodied energy datasets can be integrated into BIM models to explore the modelling and predicting of	**Rec**

			data.

[a] RC No.: Research cycle number (1-5).
[b] Adopted Methods: Adopted methods per research cycle and reference letter (for purpose of table only).
[c] Link: Link between each lessons learned and adopted methods with subsequent research (reference letter); Rec: Lessons learned considered within chapter 6 (recommendations).

4.4 Overarching Objective One

The purpose of first overarching objective was to review the current state of art surrounding initial embodied energy consumption within the UK non-domestic sector.

4.4.1 Pre Research Cycles – Sub-objectives 1.1 to 1.6

4.4.1.1 Diagnosing and Action Planning

The RE planned to develop a comprehensive industry perspective of the research subject through a critical review of industry literature, which was aligned against the content of sub-objectives 1.1 to 1.6 (section 1.4). The review intended to identify key research problems surrounding the subject which would stimulate leading questions and drive actions undertaken within subsequent research cycles.

4.4.1.2 Action Taking

The method of reviewing industry literature was selected by the RE as previous researchers highlighted the benefit of examining existing published information to support wider research context (Thomlinson, 1969; Stewart and Kamins, 1993; Fellows and Liu, 2008). The method helped identify what type of data would be required (i.e. captured and assessed) to realise the aim of the research project. The review of industry literature was undertaken in line with the methodology highlighted previously in section 3.3 and derived primarily from research papers (i.e. journal and conference papers). The review of industry literature was progressively updated throughout the research project to maintain its practical application and relevance towards the research.

4.4.1.3 Evaluating

Extensive findings from the critical review of industry literature were previously presented within chapter 2 and included within the four research papers (Appendix A to Appendix D). Table 4.8 highlights the key findings per sub-objective which helped form the basis and focus of subsequent research cycles.

Table 4.8 Key findings from the review of industry literature

Sub-Objectives	Review of Industry Literature Key Findings
1.1 UK Non-domestic sector	The UK non-domestic sector accounts for 18% of the UK's total CO_2 emissions (operational and embodied), thus reducing CO_2 emissions from the sector by 35% by 2020 could result in a financial cost saving of more than £4.5 billion for the UK economy (BIS, 2010; Carbon Connect, 2011).
1.2 Existing Methods	Life Cycle Assessment (LCA) practitioners commonly assume or even ignore certain life cycle impacts due to variation in system boundaries, calculation methods and data sources; all of which questions the accuracy, validity and usefulness of existing data (Treloar, 1997; Treloar et al., 2000; Optis and Wild, 2010; Dixit et al., 2012; Ding and Forsythe, 2013).
1.3 Relative Significance	As operational energy efficiency increases due to improved energy efficient design, embodied energy will become a more significant part of project life cycle energy (Fieldson and Rai, 2009; Gustavsson et al., 2010).
1.4 Drivers	Continued energy price rises and the introduction of carbon taxation through the Carbon Reduction Commitment (CRC) Energy Efficient Scheme has emphasised to contractors that the cost of poor energy efficiency is likely to escalate in the future (SFfC, 2010a; Carbon Connect, 2011).
1.5 Challenges	There is a deficiency of available, robust project data which provides awareness of how energy is consumed within different building types across various project life cycles especially as buildings themselves are complex in terms of form, function, life span, and end user requirements (Scheuer et al. 2003; Dixit et al. 2012; Van Ooteghem and Xu 2012; Giesekam et al., 2014).
1.6 Opportunities	Embodied impacts can be tackled during the design stage through the incorporation of waste minimisation, reduced material use, increased recycled content and specifying materials with low embodied impact per weight; all of which can also influence construction methods, operational use, maintenance cycles and building life span (Harris 1999; Chen et al. 2001; Fieldson and Rai 2009; Rai et al., 2011).

4.4.1.4 Specified Learning

The review of industry literature identified a lack of initial embodied energy data (primarily transportation and construction phase data) from construction projects as a significant challenge which has restricted awareness and application of the subject across project stakeholders including contractors to aid data capture, assessment and potential reduction of energy consumption. Hence, to improve the situation and the provision of future research, the

RE identified the following advances: improved comprehension of methods and assumptions made by practitioners within previous LCA studies; enhanced awareness of the relative significance of individual life cycle phases; and greater appreciation of the opportunities and challenges for different project stakeholders to consider initial embodied energy consumption.

4.4.2 Updated Research Progression

Figure 4.3 illustrates the progression of the research after completion of the first overarching objective and associated sub-objectives.

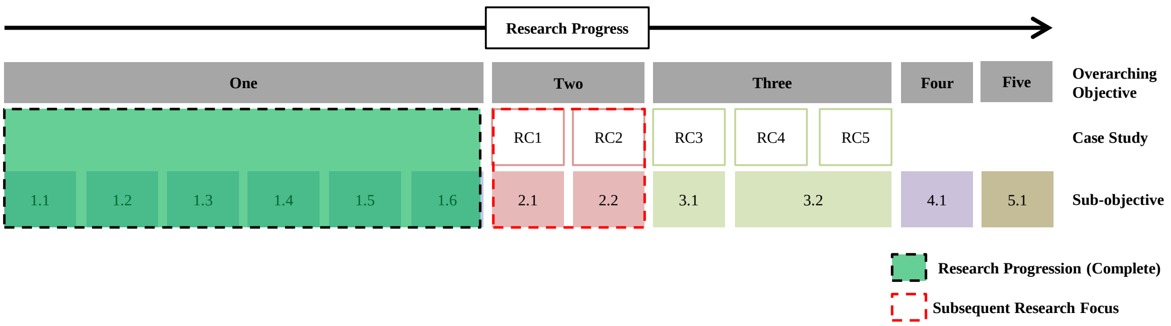


Figure 4.3 Research progress at completion of the first overarching objective

4.5 Overarching Objective Two

The purpose of the second overarching objective was to investigate current practices employed by a contractor within UK non-domestic construction projects. Two research cycles (1 and 2) were undertaken to achieve the associated sub-objectives (section 1.4).

4.5.1 Research Cycle 1 – Sub-objective 2.1

4.5.1.1 Diagnosing and Action Planning

To achieve sub-objective 2.1, the first research cycle investigated the effectiveness of contractor behaviours and current practices towards managing construction phase energy consumption within UK non-domestic construction projects. The RE planned to undertake a critical review of literature (industry and contractor), a quantitative analysis of historic contractor data, and multiple interviews with contractor operatives with regards to on-site energy management. Literature identified that contractors are principally responsible for construction phase energy consumption (Shen et al., 2005; Goggins et al., 2010; Monahan and Powell, 2011). Table 4.9 summarises context and leading questions that formed the basis of the research cycle, which concluded the first research paper presented in Appendix A.

Table 4.9 Research cycle 1 content and leading questions

Sub-Objectives[a]	Context	Leading Questions
2.1 Contractor Current Practices - CON	The contractor is principally responsible for the energy use during the construction phase (Shen et al., 2005; Goggins et al., 2010; Monahan and Powell, 2011)	- What type and level of data does the contractor already capture regarding construction phase energy performance? - How useful is historic data in predicting future construction phase energy performance? - How is construction phase energy performance currently perceived by contractor operatives?

[a] Sub-Objectives: MAT, Material life cycle phase; TRAN, Transportation life cycle phase; CON, Construction life cycle phase.

4.5.1.2 Action Taking

The adopted mixed methods were selected by the RE to facilitate a multi-dimensional view on the subject intended to progress breadth and depth of understanding and improve confidence in findings (Johnson et al., 2007; Fellows and Liu, 2008; Buchanan and Bryman, 2009). Figure 4.4 displays the relationship between the mixed methods, explored data sources and key findings.

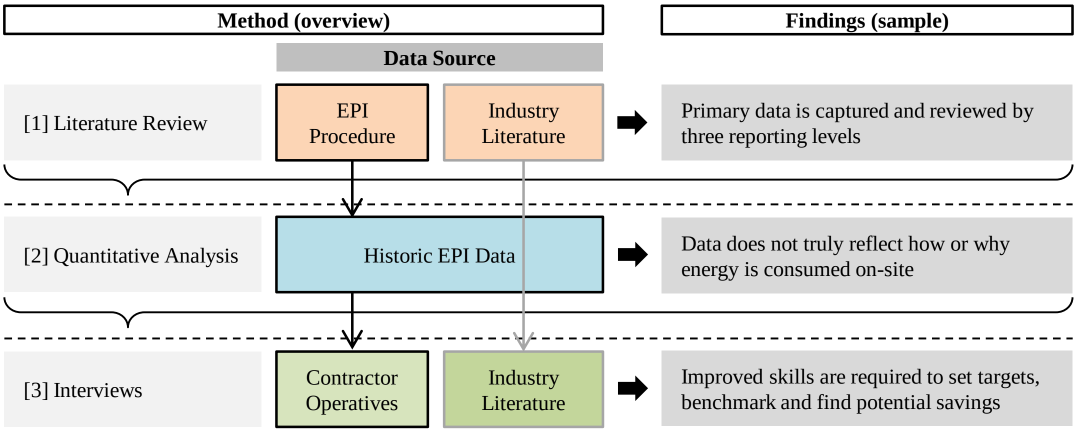


Figure 4.4 Relationship between the method and findings from the first research cycle

The critical review of literature provided both an industry-wide and internal contractor perspective on on-site energy management. The industry-wide perspective derived from the RE's review of industry literature which focused on on-site energy management drivers, current practices and the current performance of the UK non-domestic sector. The review was primarily derived from research papers and undertaken in line with the methodology previously described in section 3.3. The internal contractor perspective derived from the RE's critical review of the cross-organisational reporting procedure known as the Environmental Performance Indicator (EPI) procedure. This review derived from the RE's personal correspondence and active involvement within the contractor.

The quantitative analysis was in the form of a regression analysis which explored the usefulness of historic EPI data for predicting on-site energy consumption (i.e. electrical and red diesel usage). The idea for the analysis derived from the review of industry literature (section 2.5) and preliminary study findings (Appendix F) regarding past on-site monitoring practices. The Statistical Package for Social Science (SPSS) 19.0 software was used to evaluate the data captured from a sample of UK non-domestic construction projects in line with the methodology previously described in section 3.4. The RE created a series of multiple linear regression models to distinguish potential connections between different project types, project variables and dependent variables, which resulted in two final models (i.e. 'All Projects' and 'Project Type' specific). A comparison of each model was undertaken to determine its ability to predict energy consumption whereby differences the between the actual sampled data and the modelled data highlighted the overall degree of uncertainty (i.e. standardised residual values) within the modelled equations. An extensive overview of the development of the models is presented within paper 1 (Appendix A).

The interviews intended to build upon the evidence derived from the review of literature and quantitative analysis. In line with the methodology previously described in section 3.3 a sample of non-domestic sector operatives across each of the three EPI procedure reporting levels (Director, Operations, and Project) participated within personal semi-structured interviews to established the effectiveness of the EPI procedure towards managing on-site energy consumption data and how on-site energy management was currently perceived within the contractor. Content analysis was used to evaluate the qualitative data through the use of matrix tables and frequency counts which identified a degree of consistency with the preselected themes derived from the RE's insight and supporting research approaches.

4.5.1.3 Evaluating

From the review of industry literature, the RE discovered that previous researchers have experienced varied success when investigating energy consumption (embodied or operational) through on-site monitoring practices. Overall, the review updated the main literature review presented in chapter 2 whereby key additional findings which expanded the RE's existing knowledge are summarised in Table 4.10.

Table 4.10 Key additional findings from the review of industry literature (after Davies et al., 2013a, paper 1)

Focus	Key Additional Findings
On-site energy	- On-site construction can represent up to 7% of project life cycle energy though its influence across different aspects of project life cycle energy is unknown (Adalberth, 1997a; Cole, 1999; Lane, 2007;

management drivers	Smith, 2008; Davies et al., 2013a); - Existing industry drivers can provide opportunities for contractors to improve reporting procedures and benchmark future on-site energy use performance (BIS, 2010; Ko, 2010).
On-site energy management current practices	- Existing embodied energy inventories and methodologies are designed to help practitioners quantify and understand the multiple forms and significance of embodied energy but these are deemed to be insufficient and inaccurate (Buchanan and Honey, 1994; Alcorn and Baird, 1996; Dixit et al., 2010; BSRIA, 2011); - A previous attempt to investigate energy consumption during on-site construction via energy meter readings and fuel receipts was unsuccessful in disaggregating energy consumption per construction activity and package (Monahan and Powell, 2011); - A previous attempt to investigate operational energy performance of 25 occupied domestic buildings was successful in comparing performance against national averages, low energy benchmarks and UK regulations via the collection of on-site electrical, heat and water consumption data across a range of monitoring intervals (Gill et al., 2011).
UK non-domestic sector	- In 2008 new education and healthcare projects represented 13% and 7% respectively of the annual UK construction activity (SFfC, 2010a; BREEAM, 2011; ONS, 2011); - In 2008 the construction process produced 5.87 $MtCO_2$ whereby on-site construction was responsible for 34% (2.01 $MtCO_2$) (Ko, 2010; SFfC, 2010b); - In 2008 on-site construction emissions from the new non-domestic sector represented 28% (0.56 $MtCO_2$) where new education and healthcare projects signified 4% (0.08 $MtCO_2$) and 3% (0.05 $MtCO_2$) of the total respectively (SFfC, 2010b); - Applying the CRC carbon tax of £12/ tCO_2, new non-domestic construction projects could have resulted in a financial burden of approximately £6.72 million shared amongst all responsible organisations, with new education and healthcare projects responsible for £0.96 million and £0.6 million respectively (SFfC, 2010a; Environmental Agency, 2012).

From the review of contractor literature, the RE discovered that the contractor's EPI procedure was designed to capture project environmental performance based upon a series of indicators (i.e. energy, water, waste and timber usage) in accordance with reporting requirements addressed by the contractor's parent organisation and the Carbon Reduction Commitment (CRC) Energy Efficiency Scheme (Environmental Agency, 2012). Evidently, uncovering this procedure provided the RE with some initial assurance that the contractor was engaged with the capture and assessment of construction phase energy consumption. The procedure was managed by the contractor's Environmental and Sustainability (E&S) Team but required assistance from Divisional Directors, Regional Representatives (Regional Directors, Operational Managers or Personal Assistants) and project specific Nominated Responsible Individuals (NRI's) to ensure compliance. Through personal correspondence with the E&S Team and review of historic EPI data the RE deduced the transfer of information and highlighted the reporting requirements (milestones) of the procedure as illustrated within Figure 4.5. Further detail regarding the organisation and reporting requirements of the EPI procedure is highlighted within paper 1 (Appendix A).

Step	Reporting Requirements (milestones)
1	A generic online Excel Workbook containing a Reporting Sheet requiring project environmental performance data input was created by the E&S Team;
2	A project specific NRI completes their Reporting Sheet requirements by the first Monday of each month with the contents reviewed and authorised by the Project Manager;
3	Once completed, the data was validated by Divisional Directors and Regional Representatives and formally submitted to the E&S Team by the NRI by the following Friday;
4	Once submitted, the E&S Team critically reviewed and compared all data against values outlined within the contractors commercial web based database;
5	Differences between the database values and captured data were highlighted and communicated back to the corresponding Divisional Directors and Regional Representatives for further improvement until the 14th day (final reporting deadline) of each month.

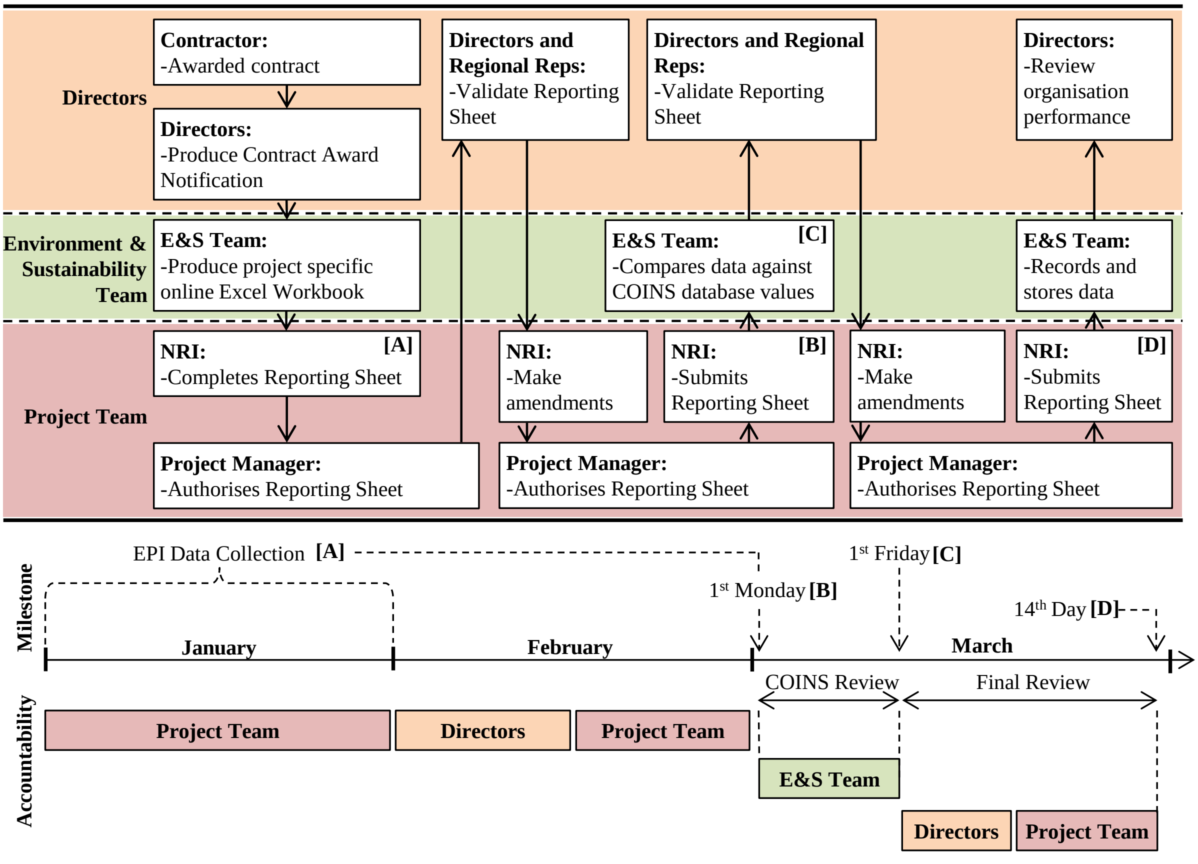


Figure 4.5 Transfer of information within the contractor's Environmental Performance Indicator (EPI) procedure (after Davies et al., 2013a, paper 1)

From the quantitative analysis, the RE discovered that both models ('All Projects' and 'Project Type' specific) experienced varied success towards predicting electrical and red diesel consumption within the sample. Comparing the residual values within both AP and PT modelled equations highlighted the significance of project type within the sampled data. Table

4.11 provides a brief overview of the findings from the comparison, where numerical reasoning which supports the table contents is displayed in paper 1 (Appendix A).

Table 4.11 Overview of findings from the model assessment

Predicting Electrical Energy Consumption[a]	Predicting Red Diesel Consumption[a]
- PT modelled equations demonstrated better consumption predictions for college and hospital projects; - AP modelled equation showing large inaccurate predictions for college and university projects; - PT modelled equations reflected accurate predictions for two school projects (Project 13 and 19) despite all variables being considerably different; - Both AP and PT modelled equations experienced major difficulty in predicting the performance of Project 15 and 22 (i.e. smallest electrical energy consumption); - The AP modelled equation outperformed the PT modelled equation when considering the largest electrical energy consuming project (Project 23).	- Both AP and PT modelled equations were unsuccessful at predicting small consumption performance; - PT modelled equations demonstrated similar prediction accuracy for hospital and university projects with the AP modelled equation reflecting large inaccurate predictions; - Both AP and PT modelled equations experienced significant difficulty in predicting consumption performance for Project 15 (i.e. few data entries); - Both AP and PT modelled equations experienced significant difficulty in predicting consumption performance for Project 5 and 16 (i.e. many data entries).

[a] Modelled Equations: AP, All Projects; PT, Project Type specific.

Generally, the PT modelled equations performed better at predicting on-site energy consumption than the AP modelled equation, as represented by the overall residual values within Table 4.12. For electrical energy consumption, the PT modelled equations demonstrated reasonable consumption predictions for college and hospital projects whereas the AP modelled equation showed large inaccurate predictions for college and university projects. In terms of red diesel consumption, the PT modelled equations demonstrated similar prediction precision for hospital and university projects whereas the AP modelled equation reflected large inaccurate predictions. Multiple electrical (6%) and red diesel (4%) data outliers were discovered within the sampled data used to formulate the two models. These outliers exceeded the normal distribution assumption parameters for standardised residual values (i.e. values outside +/-1.96) as defined in literature (Field, 2009). The cause of the outliers could not be truly substantiated from the sampled data alone, though the RE acknowledged the probable reason for some were data entry error; occasionally project variable data differed substantially from the normal trend corresponding to the specific project. Nonetheless, both models concluded a separate correlation coefficient value for each dependent variable reflecting the amount of variation in the dependent variable that was accounted for by the model based upon the entire sampled data. The AP modelled equations displayed a correlation coefficient for electrical and red diesel consumption prediction as 0.132 (13%) and 0.136 (14%) respectively. In contrast, the PT modelled equations demonstrated a correlation coefficient for electrical and red diesel consumption prediction as 0.351 (35%) and 0.277 (28%) respectively. These outcomes suggested that there was some merit towards developing PT modelled equations to predict and understand future on-site energy consumption, although 65% of electrical and 72% of red diesel consumption variability was accounted for by other project variables which were not captured within the EPI procedure. Therefore, the RE acknowledged that given its current state, the data captured within the EPI procedure would unlikely be of significant use to the contractor to formulate meaningful incentives and targets to drive reduced construction phase energy in future projects, as captured data does not reflect how or why energy is consumed during stages of project development.

Table 4.12 Comparing total residual values of all modelled equations for electrical and red diesel consumption prediction per project type (after Davies et al., 2013a, paper 1)

Sampled Data [a]				AP Modelled Equations [a]		PT Modelled Equations [a]	
Project Numbers	**Project Type**	**Electricity Actual [b]**	**R' Diesel Actual [b]**	**Electricity Residual (%)[c]**	**R' Diesel Residual (%)[c]**	**Electricity Residual (%)[d]**	**R' Diesel Residual (%)[d]**
1-3	College	2.64E+02	3.10E+01	1.39E+01	4.42E+00	3.13E+00	3.00E-02
4-8	Hospital	4.99E+02	2.27E+02	6.41E+00	9.10E+00	2.11E+00	4.83E+00
9-21	School	1.25E+03	6.40E+02	9.69E+00	7.83E+00	7.90E+00	6.38E+00
22-24	University	3.33E+02	2.61E+02	1.30E+01	1.17E+01	5.34E+00	4.47E+00
	TOTAL[e]	2.34E+03	1.16E+03	2.33E+02	1.03E+02	1.53E+02	6.35E+01
	TOTAL (%)[f]	100	100	9.94	8.85	5.76	5.48

[a] Note, all values returned to positive.
[b] Natural logarithmic values.
[c] Electricity Residual (%) = (Total Residual / Total Actual)*100.
[d] Red Diesel Residual (%) = (Total Residual / Total Actual)*100.
[e] TOTAL = Sum of Total Actuals [or] Total Residuals.
[f] TOTAL (%) = (Sum of Total Residuals / Sum of Total Actuals)*100.

From the interviews, the RE acknowledged disparity between the three EPI reporting levels (Director, Operations, and Project) in terms of on-site energy management awareness, commitment and approach. Table 4.13 displays a summary of the key findings in relation to literature whereas Table 4.14 illustrates the most common interviewee responses (relative proportion) per question topic against each EPI reporting level. Participants demonstrated vast differences in terms of knowledge and awareness of on-site energy management drivers currently influencing practices within the contractor and wider industry. In particular, project-level (PL) participants had limited perception of current UK policy, legislation and standards in comparison to director-level (DL) participants, hence some participants acknowledged no appreciation of how captured fuel consumption data disseminates and influences the actions of the wider organisation. During the interviews it was suggested by an operations-level (OL) participant that increased on-site energy management skills were required within the contractor as current responsibilities for setting targets and identifying opportunities for energy savings were inadequate. It was also suggested these responsibilities were currently shared amongst multiple individuals, instead of a dedicated energy manager as recommended in literature (Carbon Connect, 2011). The contractor established a cascade communication structure, which aimed to ensure the correct level of commitment and accountability towards on-site energy management. However, the evidence demonstrated vast unfamiliarity across the three reporting levels considering the contractor’s current electricity tariff intended to provide an improved service agreement and automated meter readers (i.e. electrical). In accordance with literature, in-depth sub-metering to capture on-site energy consumption performance was identified as a positive step forward towards improving awareness and data accuracy, although many participants throughout perceived this as too expensive and difficult to coordinate.

Table 4.13 Overview of key findings from interviews (after Davies et al., 2013a, paper 1)

Ref. [a]	S	Question Topic[b]	Key Findings[c]	Literature Context
1, 3	**D**	Awareness of current UK policy, legislation etc.	DL participants demonstrated a breath of understanding and insight whereas PL participants portrayed limited perception.	In agreement with DECC (2009a), DECC (2009b) and BIS (2010)
4	**D**	Examples of current key drivers	80% of PL participants demonstrated no awareness of the need to capture this data.	
5 - 7	**D**		DL and OL participants acknowledged numerous organisation reporting commitments.	In agreement with Ko (2010), IEMA (2010) and Carbon Connect (2011)
8	**D**	Need for capturing on-site energy consumption data	The contractor is changing behaviour and “willing to adopt more energy efficient practices” to reduce cost.	In agreement with Ofgem (2009), DECC (2010) and Morton et al. (2011)
10	**D**		PL participants acknowledged no appreciation of how data disseminates and influences wider organisation actions.	
11 - 14	**P**	Awareness of project life cycle energy	All participants understood the term operational energy but showed contrasting views with regards to embodied energy.	In agreement with RICS (2010) and Monahan and Powell (2011)
15	**P**	Delivery of on-site energy management	DL participants recognised that the contractor’s ISO14001 accreditation improves competitiveness and environmental awareness	In agreement with Biondi et al (2000) and Nakamura et al. (2001)
16, 17	**P**		OL participant recognised increased on-site energy management skills are required and current responsibilities are currently shared amongst multiple individuals.	In disagreement with Carbon Connect (2011)
18 - 21	**P**	Methods of communicating on-site energy management	Many DL and OL participants questioned the effectiveness of the contractor’s cascade communication system.	In disagreement with Vine (2008)
22	**C**	Examples of current key challenges	Too difficult to benchmark project performance due to vast incorrect, incomplete data received.	In agreement with Jones (2010)
23	**C**		All participants noted supply chain members are non-proactive with information.	In disagreement with Bansal and Hunter, (2003), Bellesi et al. (2005) and Grolleau et al. (2007)
24	**C**		On-site metering was deemed too difficult to coordinate and costly.	In disagreement with Firth et al. (2008), BIS (2010) and Ko (2010)
26	**C**		PL participants questioned the purpose and benefit of the procedure.	
27	**C**		Most participants suggested responsibility is normally forced upon less involved, inexperienced individuals.	
29	**C**		Most PL participants claimed that they neglected to follow procedure guidance and validate their data before submittal.	
32	**C**		All PL participants noted difficulty in finding time to capture the required information.	
35 - 39	**O**	Examples of current key opportunities	Assorted participants suggested capturing additional project variables could help many project stakeholders improve understanding and formulate benchmarks.	In agreement with BIS (2010), Shen and Zhang (2002) and Tan et al. (2011)

40 - 42	O		Most participants acknowledged improved reliance upon an earlier electrical-grid connection can help reduce red diesel use and improve accuracy of on-site practice.	In agreement with Ko (2010) and Monahan and Powell (2011)
45	O		PL participants revealed project teams only receive feedback (i.e. negative) when data is incorrect.	In disagreement with Stepp et al. (2009).

[a] Ref.: Response reference from interviewees keyed to Appendix A.
[b] S, Section of the interview: D, Drivers; P, Current Practices; C, Challenges; O, Opportunities.
[c] Key Findings: DL, Director Level; OL, Operations Level; PL, Project Level.

Moreover, the RE discovered conflicting opinions surrounding the significance of the EPI procedure with on-site senior management not recognising its purpose and benefit. Evidence suggested that the EPI procedure guidance and authentications were not always thoroughly considered amongst project teams, which questions the validity of the overall procedure and the ability of the historic EPI data to accurately reflect on-site energy consumption performance. To improve the usefulness of the EPI procedure, the evidence highlighted a need for additional project variables to increase the granularity of existing data and help generalise the modelled equations to predict consumption performance for projects outside the sample.

Table 4.14 Summary of most common interviewee responses (relative proportion) per question topic (after Davies et al., 2013a, paper 1)

Ref[a]	S[b]	Question Topic	Common Interviewee Responses[c]	Totals (%)[d]		
				P	O	D
1	Drivers	Awareness of current UK policy, legislation etc.	Broad awareness and understanding	0	33	67
2			Basic awareness and understanding	25	75	0
3			Limited or no awareness and understanding	100	0	0
4		Examples of current key drivers	Parent organisation reporting commitments	9	36	55
5			Carbon Reduction Commitment (CRC)	8	46	46
6			Dow Jones Sustainability Index	0	38	63
7			Carbon Disclosure Project (CDP)	0	43	57
8		Need for capturing on-site energy consumption data	Eager to adopt efficient practices to reduce fuel costs	10	40	50
9			Eager to improve value and reputation	0	44	56
10			There is limited or no requirement	100	0	0
11	Current Practice	Awareness of project life cycle energy	Broad understanding of operational energy	29	35	35
12			Broad understanding of embodied energy	0	50	50
13			Basic understanding of embodied energy	33	17	50
14			Limited or no understanding of embodied energy	50	50	0
15		Delivery of on-site energy management	ISO 14001 accreditation helped provide framework	0	17	83
16			Responsibilities shared amongst multiple individuals	22	33	44
17			Current skill set for setting targets is inadequate	0	100	0
18		Methods of communicating on-site energy	Current communication structure ensures correct commitment and accountability	0	40	60
19			Broad awareness of new electricity tariff	0	80	20

20		management	Basic awareness of new electricity tariff	33	67	0
21			Limited or no awareness of current electricity tariff	44	0	56
22	**Challenges**	Examples of current key challenges	Data currently insufficient for benchmarking purposes	0	50	50
23			Most supply chain members are non-proactive	71	29	0
24			In-depth sub-metering is costly and difficult to coordinate	25	25	50
25			EPI is important to reduce organisation environmental impact	0	67	33
26			EPI contains limited purpose and benefit	100	0	0
27			EPI responsibility is forced upon individuals	38	31	31
28			Strong H&S emphasis is not mirrored for energy management	40	40	20
29			EPI guidance is not followed and data is not reviewed	80	20	0
30			EPI contains no detailed checks for validation	100	0	0
31			Data discrepancies between EPI and COINS	100	0	0
32			Finding time to fulfil the EPI requirements	56	33	11
33			Lack of available staff on refurbishment projects	67	0	33
34			Difficult to quantify usage between mixed power supplies for refurbishment projects	80	0	20
35	**Opportunities**	Examples of current key opportunities	EPI reflects commitment to reduce environmental impact	0	0	100
36			Capture additional project variables to improve data quality	25	38	38
37			Capture additional project variables to improve understanding of energy use on-site	30	20	50
38			Benchmark performance to increase best practice etc.	9	45	45
39			Benchmark performance to enable comparison and ranking	0	50	50
40			Using red diesel generators on-site is common	29	35	35
41			Earlier electrical-grid connection can improve accuracy of data	17	42	42
42			Earlier electrical-grid connection can reduce red diesel	18	45	36
43			Improved efficient behaviour due to new electricity tariff	0	80	20
44			Improved ability to forecast earlier electrical-grid connection due to new electricity tariff	0	80	20
45			Increased feedback to improve on-site energy management awareness and approach	36	36	27

[a] Ref.: Response reference from interviewees keyed to Appendix A.
[b] S: Section of the interview.
[c] Common Interviewee Reponses: EPI, Environmental Performance Indicator Procedure; H&S, Health and Safety; COINS, Construction Industry Solutions commercial web based database.
[d] Totals: P, Relative proportion (%) of total Project Level responses; O, Relative proportion (%) of total Operations Level responses; D, Relative proportion (%) of total Director Level responses.

4.5.1.4 Specified Learning

The first research cycle explored the contractor's current practices and actions towards managing construction phase energy consumption through their EPI procedure. It was identified that historic EPI data was not consistently authenticated by project teams and did not reflect how or why energy was consumed during project development. Hence, to improve the situation and the provision of future research, the RE identified the following advances: enhanced development of data capture and validation techniques during construction; improved awareness of alternative project variables and indicators across different project life cycle phases which influence energy consumption; and improved consideration towards data benchmarking and target setting to drive reduced energy consumption during construction.

4.5.2 Research Cycle 2 – Sub-objective 2.2

4.5.2.1 Diagnosing and Action Planning

To achieve sub-objective 2.2, the second research cycle investigated the potential for contractor current practices to support an initial embodied energy assessment within UK non-domestic construction projects. Critical reviews of both industry and contractor literature were planned by the RE as industry literature identified that contractors are accountable for wider project environmental performance (BIS, 2010; Li et al., 2010; BREEAM, 2011; Tan et al., 2011). Table 4.15 summarises context and leading questions that formed the basis of the research cycle, which concluded the second research paper presented in Appendix B.

Table 4.15 Research cycle 2 content and leading questions

Sub-Objectives[a]	Context	Leading Questions
2.2 Contractor Current Practices – MAT, TRAN, CON	The contractor is accountable for wider project environmental performance (BIS, 2010; Li et al., 2010; BREEAM, 2011; Tan et al., 2011)	- What is the relative significance of individual project life cycle phases (material, transportation, construction) for different project types? - What current practices does the contractor employ during the construction phase of a project which could help assess initial embodied energy performance?

[a] Sub-Objectives: MAT, Material life cycle phase; TRAN, Transportation life cycle phase; CON, Construction life cycle phase.

4.5.2.2 Action Taking

The adopted methods originated from findings within literature (chapter 2 and section 3.2) and evolved to discover outcomes which could be built upon by subsequent methods. Figure 4.6 displays the relationship between the method type, explored data source and findings.

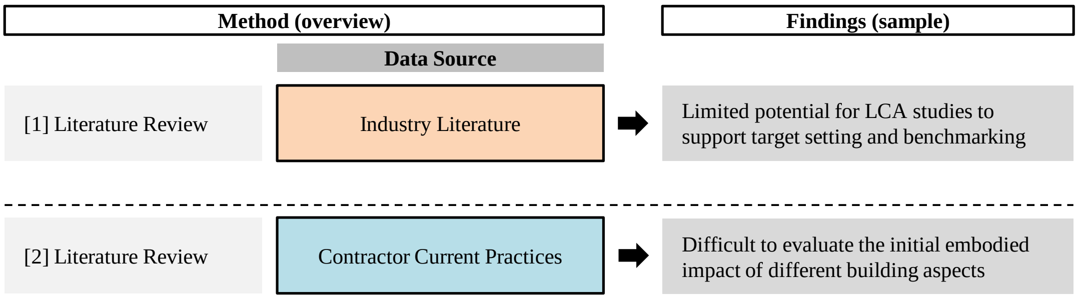


Figure 4.6 Relationship between the method and findings from the second research cycle

The critical review of industry literature provided an industry perspective on existing LCA studies. The review was primarily derived from research papers (section 3.3) and aimed to highlight the extent of existing knowledge surrounding the relative significance of individual life cycle energy phases as literature highlighted improved opportunities to reduce overall project life cycle energy could be obtained if individual life cycle phases and the relationship between them is reviewed (Optis and Wild 2010; Ramesh et al. 2010). A total of 16 existing LCA studies which focused towards initial embodied energy assessment were selected. These studies varied in terms of project scope, type and geographical location. Attempts were made to focus on non-domestic construction projects although the RE discovered that a significant proportion of existing LCA studies explored residential buildings (e.g. Adalberth 1997a; Fay et al. 2000; Chen et al. 2001; Mithraratne and Vale 2004) hence this data was also considered to potentially highlight the significance of project type. The review demonstrated the impact of total project or specific construction packages in terms of individual project life cycle phases (i.e. material, transportation, and construction), total embodied energy, or total life cycle energy levels (i.e. embodied plus operational energy) per study. A spreadsheet analysis was used to evaluate and interpret the project life cycle data extracted from the existing LCA studies to highlight trends in data (e.g. project type, location, life cycle phase energy), as presented in Appendix B.

The critical review of contractor literature appraised 6 current practices employed by the contractor during the construction phase of a UK non-domestic construction project (i.e. Project 1). This review aimed to identify the practical challenges within the current practices to support an initial embodied energy assessment within future projects. The selected current practices were deemed to contain information suitable to assess the initial embodied energy performance (e.g. material characteristics, transport vehicle type, transport distances, on-site fuel consumption), previously introduced in section 3.3. The explored UK non-domestic construction project was a design and build industrial warehouse (temperature controlled) located within the south of England (section 3.3). The RE's active involvement within the contractor provided awareness of the project and selection of current practices. Due to project availability and the duration of the research, this particular project was explored within both research cycles 2 and 3. Nonetheless, for the purpose of this research cycle, current practices were reviewed post-construction and supported through contractor queries, thus overlooking the RE's active involvement within the project. Despite previous concerns regarding the approach in literature (Peereboom et al., 1999; Menzies et al., 2007; Monahan and Powell, 2011), this approach was undertaken by the RE to determine whether sufficient comprehension could be obtained to support future research cycles and provide assurance to the contactor that this approach could be relied upon beyond the research project. A spreadsheet analysis was used to interpret the project data derived from the contractor current practices to assess the characteristics and practical challenges within the current practices (see section below).

4.5.2.3 Evaluating

From the review of industry literature, the RE discovered that limited previous LCA studies defined energy consumption relative to individual life cycle phases. The varied format of data presented within previous studies seemed to limit their use towards supporting the development of robust benchmarks and targets for energy reduction within future projects. Overall, the review which is highlighted in paper 2 (Appendix B), updated the comprehensive review previously presented in chapter 2. A summary of the key findings which built upon the previous review and improved the RE's knowledge are summarised in Table 4.16.

Table 4.16 Summary of key findings from review of existing LCA studies (after Davies et al., 2013b, paper 2)

Ref.	Key Findings	Literature Context
1	Limited studies specifically highlighted impacts relative to individual project life cycle phases, especially initial embodied energy phases.	
2	Impact of transportation and construction phase energy was deemed as small in comparison to material phase energy.	In agreement with Adalberth (1997a), Cole (1999), Chen et al. (2001) and Gustavsson et al. (2010)
3	Each study differed significantly in terms of key parameters such as the selection of system boundaries, calculation methods and data sources.	In agreement with Optis and Wild (2010) and Dixit et al. (2012)
4	A wide range of inconsistent values were used to portray the significance of initial embodied energy relative to total project life cycle energy across assorted project types.	In agreement with Scheuer et al. (2003) and Huberman and Pearlmutter (2008)

From the review of contractor literature, the RE discovered that the type and level of data captured within the current practices did not seem to truly reflect initial embodied energy consumption of the project; as inconsistencies within the data were discovered. Evidently, the lack of a clear relationship between data, sub-contractors and construction activities questioned the possibility of the current practices reflecting the significance of potential design changes or being used to formulate energy reduction targets (BIS 2010; Halcrow Yolles, 2010). The key findings derived from each of the apprised current practices are represented in Table 4.17 and Table 4.18 whereby further information on the findings per current practice is described in paper 2 (Appendix B).

Table 4.17 Findings and illustration of each contractor current practice (Table 1 of 2) (after Davies et al., 2013b, paper 2)

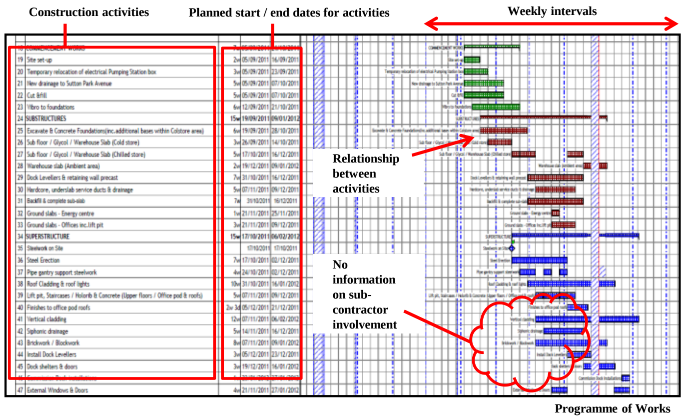
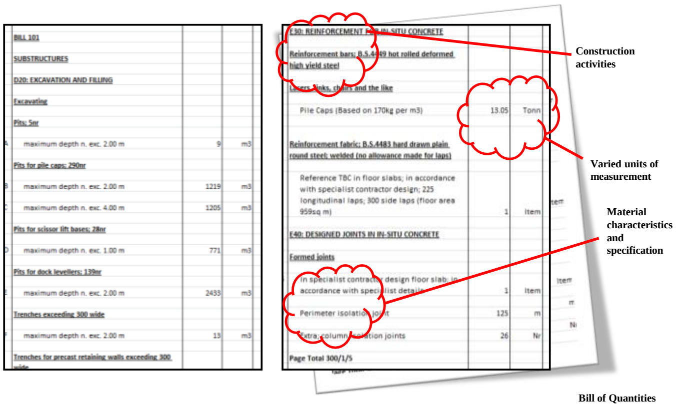
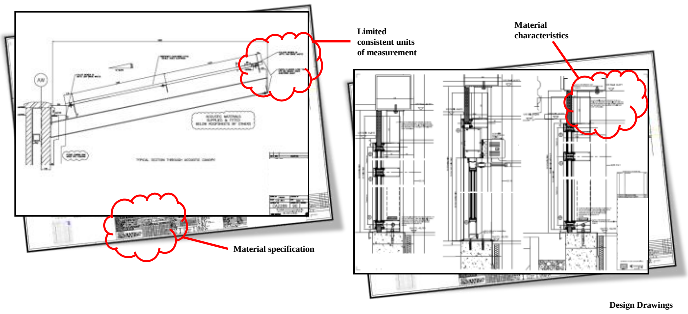
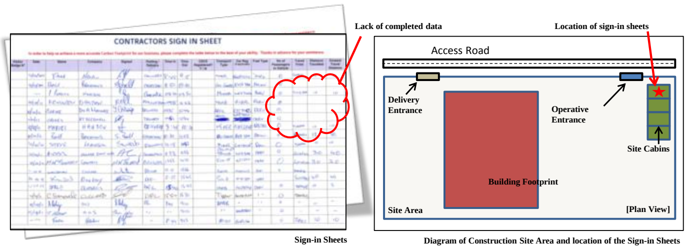
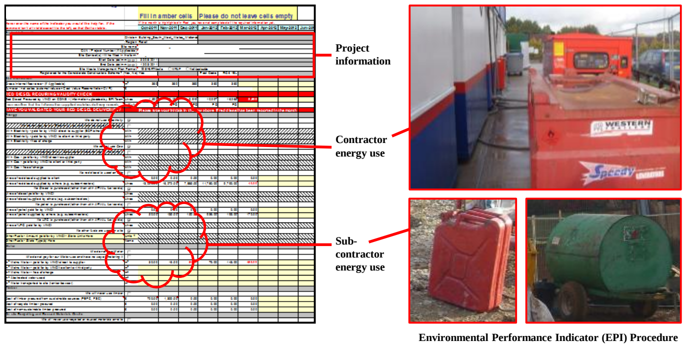
Name, Purpose and Findings	**Illustration of each Current Practice**
[1] Programme of Works (PoW) - Used to coordinate the development and delivery of the project; - No direct link between the construction activities and the sub-contractors responsible for their completion within the PoW; - PoW only current practice to capture data relative to construction activities not sub-contractors; - Limited use to help coordinate the capture of data relative to certain construction activities.	
[2] Plant Register - Used to document the operational performance of on-site plant and equipment; - Information varied significantly in terms of content, detail, legibility and terminology; - No clear correlation between the plant and equipment used and the specific construction activities undertaken by the sub-contractors.	
[3] Bill of Quantities (BoQ) - Used to coordinate project cost and provide information on material characteristics and specification; - Characteristics displayed in no consistent format (i.e. mm, m, m^2, m^3, tonne, kg) hence conversions were required to compare against data within existing LCA studies.	
[4] Design Drawings - Used to coordinate project design and provide information on material characteristics and specification; - Characteristics displayed in no consistent format (i.e. mm, m, m^2, m^3, tonne, kg) hence conversions were required to compare against data within existing LCA studies.	

Table 4.18 Findings and illustration of each contractor current practice (Table 2 of 2) (after Davies et al., 2013b)

Name, Purpose and Findings	**Illustration of each Current Practice**
[5] Sign-in Sheets - One version used to capture operative man-hours, man-days per sub-contractor; - One version used to capture visitor and material transport to and from site; - Both versions captured a varied degree of complete, valid information; - Both sheets were located within the on-site accommodation but material delivery entrance was located other side of site.	
[6] Environmental Performance Indicator (EPI) Procedure - Used to assess fuel consumption during on-site construction; - Vast ambiguity surrounding sub-contractor data in terms of the quantity of fuel delivered, when fuel was delivered and how much fuel was consumed during periodic intervals.	

4.5.2.4 Specified Learning

The second research cycle explored the potential for contractor current practices to support an initial embodied energy assessment through the appraisal of 16 previous LCA studies and 6 current practices. It was identified that previous LCA studies demonstrated limited consistency in terms of key parameters (i.e. system boundaries, calculation methods, data sources) which potentially diminished their use to support energy reduction targets for future projects. Furthermore, the type and level of data captured within the current practices was deemed inconsistent and did not truly reflect project initial embodied energy consumption. Hence, to improve the situation and the provision of future research, the RE identified the following advances: enhanced consistent approach towards the capture of project data across individual initial embodied energy phases (i.e. material, transportation and construction); increased awareness of data associations between construction packages, construction activities and sub-contractors; and improved consideration of the relationship between individual life cycle phases.

4.5.3 Updated Research Progression

Figure 4.7 illustrates the progression of the research after completion of the second overarching objective and associated sub-objectives and case studies.

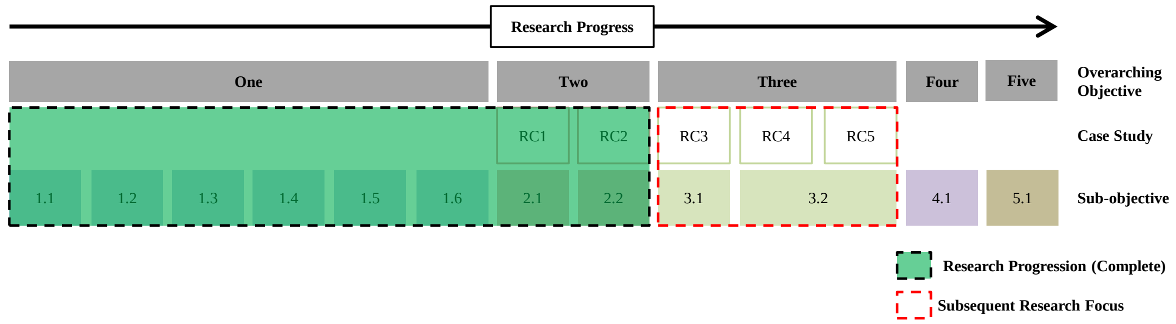


Figure 4.7 Research progress at completion of the second overarching objective

4.6 Overarching Objective Three

The purpose of the third overarching objective was to explore a practical framework to support the assessment of initial embodied energy consumption within UK non-domestic construction projects. Three research cycles (3, 4 and 5) were undertaken to achieve the associated sub-objectives (section 1.4) whereby the relationship between the research cycles in terms of framework development and exploration is illustrated within Figure 4.8.

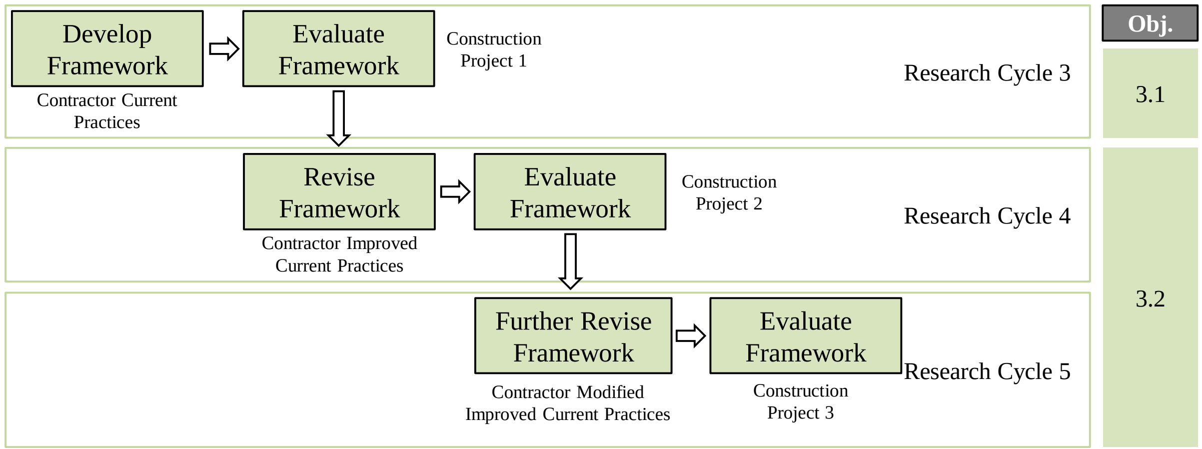


Figure 4.8 Relationship between sub-objectives and framework development for research cycles 3 to 5.

4.6.1 Research Cycle 3 – Sub-objective 3.1

4.6.1.1 Diagnosing and Action Planning

To achieve sub-objective 3.1, the third research cycle developed a practical framework for an initial embodied energy assessment within UK non-domestic construction projects. The RE planned to undertake a critical review of literature (industry and contractor) and a case study accompanied by a quantitative analysis of primary data from a live construction project. In particular, the review of contractor literature was intended support the development of the practical framework. Literature indicated contractors have access to primary data associated to initial embodied energy due to their significant role in project procurement and delivery (Goggins et al., 2010; RICS, 2010; BREEAM, 2011; Monahan and Powell, 2011; Wong et al., 2013). For the purpose of the research project, the practical framework was regarded as an integrated and structured assessment model designed to aid comparison of data to meet a predetermined objective (Gasparatos, 2010; Srinivasan et al., 2014). The key content of the framework, and instructions for use, is displayed in detail within Appendix J. Table 4.19 summarises context and leading questions that formed the basis of the research cycle, which concluded the third research paper presented in Appendix C.

Table 4.19 Research cycle 3 content and leading questions

Sub-Objectives[a]	Context	Leading Questions
3.1 Develop Practical Framework	The contractor has a vested interest in initial embodied energy due to their significant involvement in project procurement, pre-construction and on-site construction activities (BIS, 2010; Li et al., 2010; RICS, 2010; Tan et al., 2011)	- What project life cycle phases and associated embodied energy indicators are typically considered within LCA studies? - What type and level of data does the contractor already capture associated with the energy performance of individual project life cycle phases? - What is the relative significance of individual project life cycle phases (material, transportation, construction) for a specific UK non-domestic construction project?

[a] Sub-Objectives: MAT, Material life cycle phase; TRAN, Transportation life cycle phase; CON, Construction life cycle phase.

4.6.1.2 Action Taking

A mixed methods approach was adopted to facilitate a multi-dimensional view on the subject. The adopted methods stemmed from the previous review of industry literature (chapter 2) and existing procedure (section 3.2). Previous similar studies have recommended a case study approach to explore project data in the form of an LCA, due to its ability to capture in-depth data drawn from a large number of project variables and researcher experience and practice. Within this research cycle, the RE included additional techniques to support the case study approach to improve its appropriateness in relation to the research project aim. Figure 4.9 displays the relationship between the method type, explored data source and findings.

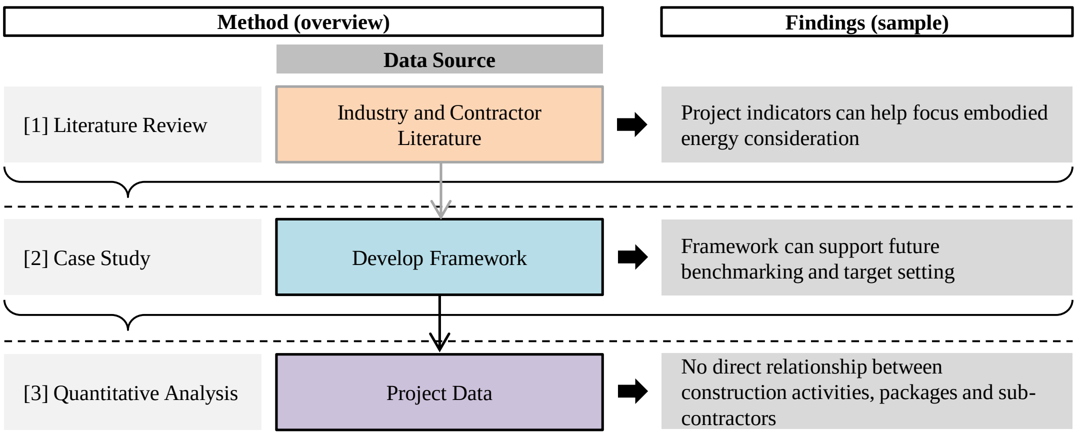


Figure 4.9 Relationship between the method and findings from the third research cycle

The critical review of industry literature provided an industry perspective on existing LCA studies. The review was primarily derived from research papers (section 3.3) and aimed to highlight the type and level of data needed to assess total initial embodied energy consumption of a project (Treloar et al., 2000; Ding and Forsythe, 2013). This review updated the previous review presented within research cycle 2, which focused on the relative significance of individual life cycle energy phases (i.e. the findings) whereas this particular review focused on the key parameters of an LCA study (i.e. the method). In particular 25 existing LCA studies were reviewed which varied in terms of research scope, system boundaries, calculation methods, data sources, project types, and geographical locations. Similar to the previous industry literature review (section 4.5.2), domestic and non-domestic projects were considered by the RE to distinguish potential significant differences data due to project type (Fay et al., 2000; Gustavsson et al., 2010; Monahan and Powell, 2011).

The RE built upon the preceding review by undertaking a critical review of contractor literature which derived a practical framework to support an initial embodied energy assessment. The framework was designed to overcome common weaknesses within LCA studies in terms of data completeness and consistency (Treloar et al., 2000; Van Ooteghem and Xu, 2012; Basbagill et al., 2013). The RE reviewed 8 current practices commonly used by the contractor during the construction phase of a UK non-domestic construction project (Project 1). The selection process and characteristics of the current practices and construction project was previously introduced in section 3.3. Active involvement and correspondence with contractor operatives enabled the RE determine a sample of construction packages to be investigated within the construction project.

The RE undertook a case study in the form of an observational technique and quantitative analysis which explored the practical framework (derived from the previous review) within a live construction project. The case study aimed to evaluate all initial embodied energy phases (i.e. material, transportation, and construction phases) which existing LCA studies either overlooked or assumed respective data (e.g. Gustavsson et al., 2010, Halcrow Yolles, 2010). Non-intrusive participant observation was used to capture a detailed account of primary data from the contractor's actions and practices within the explored construction project (i.e. Project 1). Data was captured during different intervals throughout the construction phase of the project. For instance, material characteristics (e.g. dimensions and specification details) within the design drawings was extracted when made available (i.e. drawings deemed complete and approved for construction by the project team) whereas data within the sign-in sheets (e.g. distance travelled, mode of transport) was obtained weekly due to their frequent use on-site. Capturing data at different intervals provided the RE an opportunity to process data and not to interfere with the workings of the contractor, as the current practices were considered as live documents (i.e. continually changing). Table 4.20 outlines how data was captured per project life cycle phase. Multiple Microsoft Excel spreadsheets were used to assess the captured data in line with the methodology previously described in section 3.4. To allow the results to be easily compared in future studies, the RE considered both embodied energy and carbon (i.e. CO_2) during the analysis; as literature identified these terms as interlinked (Dakwale et al., 2011; Dixit et al., 2012).

Table 4.20 Overview of data capture approach per project life cycle phase (after Davies et al., 2014, paper 3)

Initial embodied energy phase data	Approach to data capture[a]
Material phase data	- Each construction package consisted of smaller construction activities which included many different types and quantities of materials; - Materials assessed via ICE material database (Goggins et al., 2010; Rai et al., 2011); - Data correlated against the material characteristics within the BoQ's and design drawings (Scheuer et al., 2003; Kofoworola and Gheewala, 2009; Chang et al., 2012).
Transportation phase data	- Values such as distance travelled and vehicle type from the current practices (e.g. sign-in sheets) were applied to conversion factors within the Defra Guide (Williams et al., 2011; DEFRA, 2012); - Contractor operative's support was required during data inadequacies.
Construction phase data	- EPI Procedure enabled fuel type and quantities to be captured from sub-contractors on a monthly basis; - Values (e.g. fuel type) were applied to conversion factors within the Defra Guide (DEFRA, 2012).

[a] Methods: ICE, Inventory of Carbon and Energy; BoQ, Bill of Quantities; EPI, Environmental Performance Indicator Procedure.

4.6.1.3 Evaluating

From the review of industry literature, the RE identified significant differences across previous LCA studies with regards to adopted methodology. Despite the importance of establishing a well-defined system boundary to facilitate useful captured data (Crawford, 2008; Optis and Wild, 2010; Dixit et al., 2012), RE acknowledged difficulty in comparing LCA data due to flexible system boundaries used by researchers (Kofoworola and Gheewala, 2009). The process-based method was recognised as the most widely used calculation method (Emmanuel, 2004; Pearlmutter et al., 2007), though issues regarding system boundary truncation were common which caused, in some cases, significant errors in data (e.g. Crawford, 2009). The value of using existing datasets (e.g. ICE material database) to support research was reflected in some studies (e.g. Fieldson and Rai, 2009; Rai et al., 2011), though the use of incomplete, non-validated secondary source data caused uncertainty and variability in findings (Peereboom et al., 1998). Hence, the RE recognised the need for an improved standardised approach to support project decision making regarding initial embodied energy consumption (BIS, 2010; Dixit et al., 2012; Van Ooteghem and Xu, 2012) which formed the basis of the practical framework (see below). Overall, the review which is highlighted in paper 3 (Appendix C), updated the comprehensive review previously presented in research cycle 2 (section 4.5.2). A summary of the key findings which built upon the previous review and improved the RE's knowledge are summarised in Table 4.21.

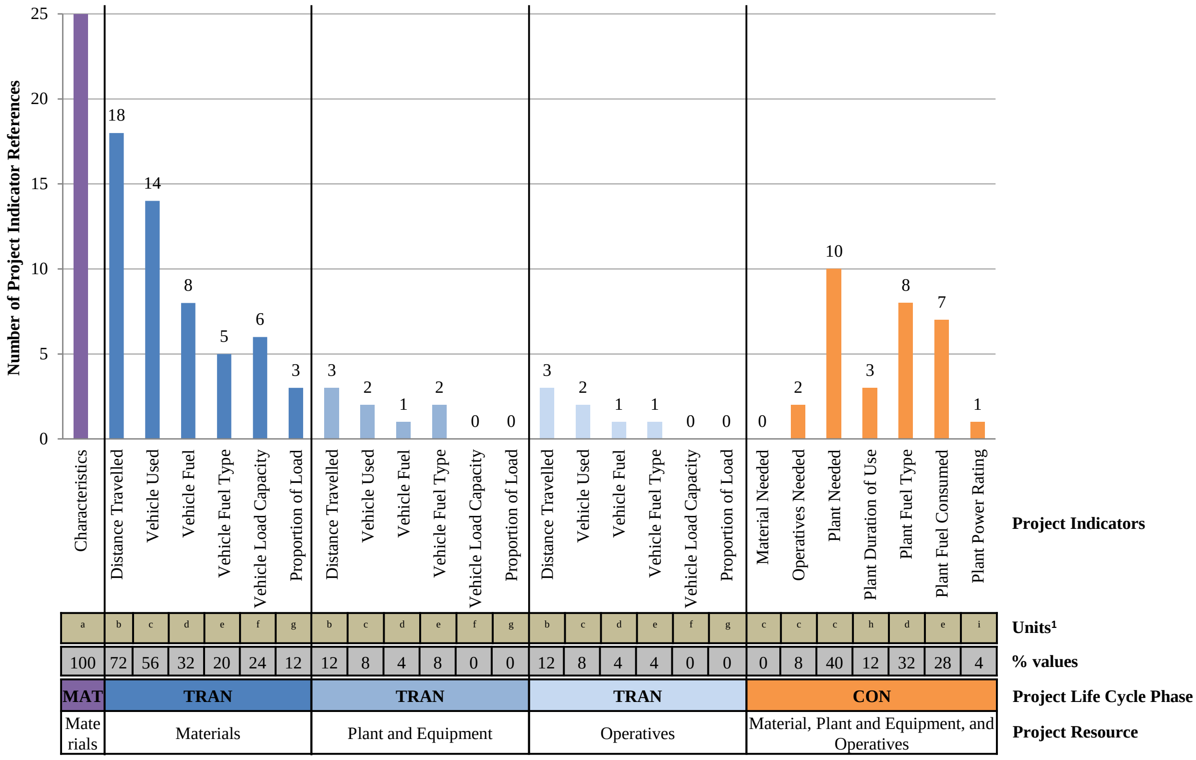
Table 4.21 Key findings from the review of industry literature within the third research cycle (after Davies et al., 2014, paper 3)

Focus	Key Findings
Project life cycle energy	- Existing LCA studies have primarily focused towards addressing operational energy (Gustavsson et al., 2010); - Some studies have highlighted the significance of operational energy (Van Ooteghem and Xu, 2012) whereas other studies (Pearlmutter et al., 2007) have questioned its dominance for all project types; - Attempts to reduce operational heating requirements through super-insulated windows and walls could lead to increased material and transportation phase impacts (Sodagar and Fieldson, 2008; Blengini and Di Carol, 2010; Optis and Wild, 2010; Menzies, 2011); - Material phase energy is derived from the procurement and manufacture of materials (Cole, 1999; Dixit et

	al., 2010; Davies et al., 2013a; Davies et al., 2014); - Transportation phase energy is derived from the transportation of materials, plant and equipment and operatives to and from site (Cole, 1999; Dixit et al., 2010; Davies et al., 2013a; Davies et al., 2014); - Construction phase energy is derived from on-site construction and assembly (Cole, 1999; Dixit et al., 2010; Davies et al., 2013a; Davies et al., 2014).
LCA system boundaries	- System boundary selection defines the number of inputs considered within an assessment; - A well-defined boundary improves the usefulness of captured data (Crawford, 2008; Optis and Wild, 2010; Dixit et al., 2012); - Difficult to compare LCA's due to flexibility in designing system boundaries (Kofoworola and Gheewala, 2009).
LCA calculation methods	- The cycle inventory (LCI) analysis is a reflection of the general quality an assessment; - Quantifies the input and output flows for a particular product or process (Scheuer et al., 2003; Crawford, 2008). - The process-based method is the most widely used LCI method whereby energy requirements of a particular process or product is calculated from all material, equipment and energy inputs (Emmanuel, 2004; Pearlmutter et al., 2007); - The process-based method suffers from system boundary truncation (Pullen, 2000; Stephan et al., 2012); - The economic input-output (I-O) based method is a top-down technique which focuses on financial transactions (Treloar, 1997; Emmanuel, 2004; Crawford, 2008; Stephan et al., 2012); - The I-O method has limitations surrounding the age of input-output tables, use of national averages, and the conversion from economic data to energy data (Lenzen, 2001; Treloar et al., 2001b); - The hybrid-based method combines features of both process and I-O based methods (Bullard, et al., 1978; Bilec et al., 2010; Jang et al., 2015); - The hybrid-based method uses the principles of a process-based method until gaps emerge within data which are filled by the use of an I-O based method (Kofoworola and Gheewala, 2009; Chang et al., 2012).
LCA data sources	- Databases are designed to help practitioners understand and quantify project life cycle impacts; - Previous studies have indicated the use of incomplete, non-validated secondary source data can lead to uncertainty and variability in results (Peereboom et al., 1998; Janssen, 2014); - Need for a standardised approach for capturing and assessing embodied impacts in order to develop legitimate, high-quality data to better support the decision making process (BIS, 2010; Dixit et al., 2012; Van Ooteghem and Xu, 2012).
LCA assumptions	- Primary data is normally captured from design drawings, performance specifications, bill of quantities, on-site measurements and records (Scheuer et al., 2003; Kofoworola and Gheewala, 2009); - Due to data complications, sensitivity issues and the complex nature of construction projects practitioners commonly assume or even ignore certain data (Cole, 1999; Norris and Yost, 2002; Gustavsson et al., 2010; Halcrow Yolles, 2010).

A quantitative analysis in the form of a spreadsheet analysis was used to organise and compare data within the 25 previous LCA studies. The RE concluded a series of project indicators (twenty-six in total) which were commonly acknowledged (either captured or assumed) within the existing LCA studies relative to different project life cycle phases. The RE organised the project indicators in terms of project resources (i.e. materials, plant and equipment, and operatives) across the different project life cycle phases, which helped focus the capture of data with the framework (see below). A detailed account of the project indicator selection and their relationship with each explored study is addressed in paper 3

(Appendix C). Figure 4.10 illustrates the frequency of project indicator references within the studies derived from the spreadsheet analysis. Evidently, 100% of the studies considered material phase energy whereas only 40% (e.g. Cole, 1999; Scheuer et al., 2003, Li et al., 2010) acknowledged construction phase energy. Interestingly, 72% of the studies considered the transportation of materials whereas impacts derived from the transportation of plant and equipment and operatives were commonly overlooked (e.g. Emmanuel 2004; Rai et al., 2011). On reflection of the previous LCA studies, the importance of material phase energy and the simplicity of capturing material phase data were made apparent to the RE. None of the explored previous LCA studies referenced all project indicators (twenty-six) due to considerations towards different key parameters (e.g. system boundaries), though Cole (1999) referenced the most (twenty).



[1] Project Indicator Units: a (type, no., m^2, m^3, tonne); b (miles, km); c (type, no.); d (petrol, diesel, etc.); e (litres, kWh); f (tonne, m^3); g (%); h (hrs, days); i (v, a, watts).

Figure 4.10 Quantitative summary (no. and %) of project indicator references within the existing LCA studies per project life cycle phase

Building upon the previous adopted method, the review of contractor literature helped the RE develop the practical framework. The framework was based upon five key sections, which were: principles, indicators, structure, equations, and alignment. Each section was created to define a particular key function of the framework with regards to data, which was as follows:

- The *principles* section outlines how data was explored;
- The *indicators* section outlines what data was captured;
- The *structure* section outlines how data was organised;
- The *equations* section outlines how data was assessed;
- The *alignment* section outlines what and how data was sourced.

Table 4.22 summarises the characteristics and findings from the development of the framework. Further information is defined in paper 3 (Appendix C). Essentially, the framework was intended to help RE capture and assess detailed initial embodied energy data from construction packages, activities and sub-contractors across individual life cycle phases. To ensure the usefulness of the framework, the RE selected a hybrid-method which enabled the framework to utilise primary data available to the contactor (e.g. energy consumed on-site), and secondary data unavailable to the contractor (e.g. energy consumed during material manufacture). To support data reliability, in comparison to previous studies the RE captured all project indicators (twenty-six) which intended to limit data assumptions and improve data consistency within the framework and potential future studies. To increase data granularity, the RE captured data across a three-tier structure intended to identify the significance of individual life cycle phases and improve upon previous LCA studies. To aid data relationships within the framework, the RE created equations designed to assess and link data between the project indicators and structure to define energy consumption per construction package, activity and sub-contractor. The review of contractor current practices, previously introduced in section 3.3, completed the final section of the framework and highlighted how data would be sourced. To provide external validity of the framework, the RE captured data primarily from current practices deemed common to most UK contractors (e.g. PoW, plant register, sign-in sheets) with the exception of some practices specific to the contractor (e.g. EPI procedure). With regards to internal validity, professional judgement was used by the RE to ensure the purpose, presentation, and content of the framework was in line with the topic in question (i.e. sub-objective 3.1) and simple clear instruction was provided to support future research (Appendix J). Furthermore, in line with the key parameters which influence the proceedings of an LCA assessment (Treloar et al., 2000; Optis and Wild, 2010; Dixit et al., 2012; Cabeza et al., 2013; Ding and Forsythe, 2013), within the developed practical framework the indicators section provided evidence of the selected system boundaries, the equation section demonstrated the calculation method adopted, and the alignment section outlined the data sources used; all of which was needed to be established to define and action the initial embodied energy assessment.

Table 4.22 Summary of the characteristics and findings from each key section of the framework (after Davies et al., 2014, paper 3)

Key Sections of the Framework	Characteristics and Findings
Principles	- Based upon the principles of a hybrid-based method; - Allow the use of primary and secondary sourced data (Cole, 1999; Gustavsson et al., 2010; Halcrow Yolles, 2010; Janssen, 2014); - Process-based analysis method to capture transportation and construction phase energy (Kofoworola and Gheewala, 2009; Chang et al., 2012); - Secondary source data (ICE material database) to evaluate material phase energy (BSRIA, 2011).
Indicators	- Organised in terms of project resources used across the three project life cycle phases; - All indicators noted in literature were incorporated within the framework structure to increase granularity of results and tackle common assumptions; - Additional indicators included where RE felt appropriate (e.g. vehicle load capacity for plant and equipment transport); - See paper 3 Table 2 for list of indicators.
Structure	- Designed to facilitate the capture and assessment of data via a three-tier structure; - Helped highlight the significance of each project life cycle phase and data weaknesses; - Displays the relationship between each project resource (i.e. material, plant and equipment, and operatives) and their impact relative to each project life cycle phase; - See paper 3 Figure 2 for diagram of structure.
Equations	- Developed to assess captured data and provide the link between the indicators and structure; - Helped assign data to specific life cycle phases (material, transportation and construction),

	construction packages and construction activities to produce a holistic overview; - Reflect material, transportation, construction and total initial embodied energy performance; - See paper 3 for series of equations.
Alignment	- Current practices captured assorted project data during different intervals to aid management of the project; - Bill of Quantities captured information on MAT type and quantity per sub-contractor; - Design Drawings captured information on MAT specification, detail and measurement per sub-contractor; - Resource Database captured information (e.g. daily, weekly or monthly) on MAT, P&E, OPP values per sub-contractor; - Plant Register captured information on P&E type and quantity per sub-contractor; - Environmental Performance Indicator procedure captured information (e.g. monthly) on fuel type and quantity per sub-contractor; - Sign-in Sheets captured information (e.g. daily, weekly or monthly) on OPP values per sub-contractor; - Sign-in Sheets captured information (e.g. daily, weekly or monthly) on transportation type, distance travelled, and fuel type for MAT, P&E, OPP movements per sub-contractor; - Programme of Works captured information (e.g. daily, weekly or monthly) on construction package and activity duration; - Site Waste Management Plan captured information (e.g. daily, weekly or monthly) on MAT waste consumption per sub-contractor; - Site Waste Management Plan captured information (e.g. daily, weekly or monthly) on transportation type, distance travelled, and fuel type for MAT waste per sub-contractor; - See paper 3 Table 4 for alignment between indicators and current practices.

From the use of the practical framework within Project 1, the ground and upper floors, external slab and frame construction packages were found to be the most significant in terms of material phase energy; which confirmed findings from literature (Halcrow Yolles, 2010). Variation was recognised across the material rates (i.e. embodied energy coefficients) used to assess the respective materials within each construction package. As previously highlighted in section 3.4, a value of ±30% was used to reflect an average degree of uncertainty across all material rates, though from the findings, in some cases this value could have been higher. For instance, there was a high degree of uncertainty within the ICE material database for the material rate for steel fibre-reinforced concrete (i.e. the ground and upper floors construction package) (BSRIA, 2011). From the review of the database, the size of the uncertainty likely stemmed from the lack of data sources supporting the overall reported material rate and the constituent materials (e.g. cement, sand, aggregates, and steel-fibre). Hence, using a larger degree of uncertainty (e.g. ±50% as recommended for some cases within the database) would have concluded different upper and lower bound limits (i.e. maximum and minimum values) for the ground and upper floors construction package, as displayed within Table 4.23. Moreover, Figure 4.11 displays the impact the change in uncertainty (i.e. measurement error) had on the relative significance of the upper and ground floor construction package in comparison to all other packages. Using the larger degree of uncertainty, the significance of the construction package varied between 56% and 30% in relation to total material phase energy.

Table 4.23 Comparison between material rate uncertainties used for ground and upper floors construction package calculations

Construction Package	Material Type	Material Quantity (kg)[a] [±10%][d]		Material Rate (MJ/kg)[a] [±Vary%][d]		Total Initial Embodied Energy (MJ)[b] [±Vary%][d]	Material Rate Lower Bound Limit (MJ)[c]	Material Rate Upper Bound Limit (MJ)[c]
Ground Floor	Concrete	3.14E+07	x	7.75[e]	=	2.43E+08	5.43 MJ/kg	10.1 MJ/kg
Ground Floor	Concrete	3.14E+07	x	7.75[f]	=	2.43E+08	3.88 MJ/kg	11.6 MJ/kg
Difference in Material Rates[g]							28% decrease	15% increase

[a] Measured values: represent the material quantities and rates derived from on-site current practices and the ICE material database.
[b] Total initial embodied energy: derived from multiplying the material quantity with the material rate.
[c] True values: represent the potential lowest and highest calculated values for the measured values (i.e. material rates).
[d] Error: represent the potential measurement error based upon the measured values defined as a percentage (i.e. relative uncertainty).
[e] Error: 30% error in material rate.
[f] Error: 50% error in material rate.
[g] Difference: % change in bound limits (from 30% error to 50% error value).

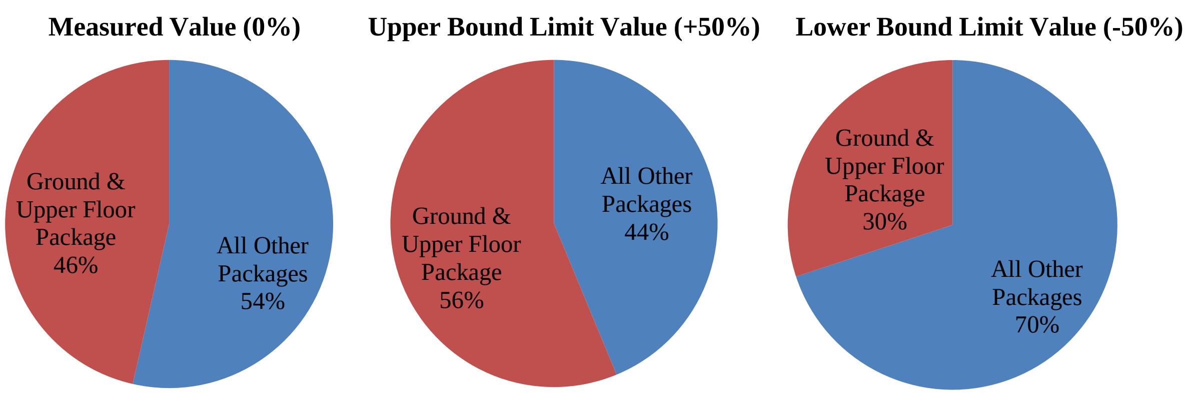


Figure 4.11 Change in relative significance for ground and upper floor construction package caused by different material rate uncertainties

In terms of the transportation phase, only data derived from the contractor's plant and equipment movements (i.e. site cabins, fuel deliveries and waste skip movements) were captured, which is addressed below. Interestingly, the distance travelled to site for skip movements was similar to the assumed value (i.e. 20 km) previously used by Adalberth (1997b). In terms of the construction phase, it was recognised that the groundworks package was responsible for the most operative man days and fuel consumption as the package was derived from multiple physical and labour-intensive activities. Evidently this positive relationship was not reflected in the earthworks package as each operative was responsible for approximately 72 litres of red diesel consumption per day as opposed to 14 litres for the groundworks package. A detailed account of findings relative to each initial embodied energy phase is provided within paper 3 (Appendix C).

Table 4.24 summarises the total measured values discovered by the RE and the corresponding degree of uncertainty (i.e. measurement error) in relation to the lower and upper bound limits for each individual life cycle phase. The results emphasised the importance of steel and concrete-based materials as the ground and upper floor, external slab and frame were the most significant construction packages (Scheuer et al., 2003; Gustavsson and Sathre, 2006; Jiao et al., 2012; Wu et al., 2014). This finding was expected considering the volume and type of material needed to traditionally support the main function of the building type; provide a durable working environment (i.e. surface) for the transportation and storage of goods. Evidently, in most cases there was a positive relationship between the significance of material phase energy and the overall ranking of each construction package. Though there was not direct link found between material phase energy and construction phase energy consumption. In once extreme case, the external slab construction package was ranked 2nd in terms of material phase energy but 17th (i.e. last) in terms of construction phase energy, as only a small proportion of fuel (e.g. petrol) was consumed on-site to facilitate concrete pumping and steel reinforcement forming (i.e. cutting, bending, and connecting).

Table 4.24 Total initial embodied energy consumption per construction package (Project 1)

Construction Package	Material Phase	Transportation Phase			Construction Phase	Total	Overall Rank
		Materials	Plant and Equipment	Operatives			
Gro & Upper Floor	5.74E+04	-	-	-	1.88E+01	5.74E+04	1st
External Slab	2.31E+04	-	-	-	5.82E-01	2.31E+04	2nd
Frame	1.67E+04	-	-	-	4.41E+01	1.67E+04	3rd
Ext' Walls & Roof	7.33E+03	-	-	-	3.70E+01	7.36E+03	4th
Racking	5.49E+03	-	-	-	4.52E+00	5.49E+03	5th
Cold Store Walls	3.68E+03	-	-	-	2.28E+00	3.68E+03	6th
Groundworks	2.66E+03	-	-	-	6.34E+02	3.30E+03	7th
Earthworks	2.57E+03	-	-	-	1.48E+02	2.72E+03	8th
Elec' & Mechanical	2.08E+03	-	-	-	5.64E+00	2.08E+03	9th
Sprinklers	1.28E+03	-	-	-	1.42E+01	1.29E+03	10th
Main Contractor	0.00E+00	-	5.18E+02	-	4.97E+02	1.01E+03	11th
Dock Levellers	6.31E+02	-	-	-	3.32E+00	6.34E+02	12th
Retaining Walls	4.50E+02	-	-	-	5.29E+00	4.55E+02	13th
Internal Walls	1.57E+02	-	-	-	1.20E+00	1.59E+02	14th
Foundations	5.81E+01	-	-	-	8.19E+00	6.63E+01	15th
Refrigeration	3.78E+01	-	-	-	1.07E+01	4.85E+01	16th
Syphonic Drainage	1.22E+01	-	-	-	4.39E+00	1.65E+01	17th
Totals (Measured)[a]	1.24E+05	-	5.18E+02	-	1.44E+03	1.26E+05	
Tot' (Lower Limit)[a]	8.41E+04	-	3.52E+02	-	9.79E+02	8.53E+04	
Tot' (Upper Limit)[a]	1.63E+05	-	6.84E+02	-	1.90E+03	1.66E+05	

[a] Totals: Measured, measured value discovered from Project 1 data (i.e. table data); Lower Limit, lowest possible value (i.e. -32%); Upper Limit, highest possible value (i.e. +32%).

Table 4.25 displays the range of total initial embodied energy consumption values per individual life cycle phase due to errors within the measured values (i.e. quantities and rates). Considering the maximum and minimum errors for each individual life cycle phase (i.e. material, transportation and construction), which are presented as the upper and lower bound limits (i.e. +32% and -32% respectively), the RE discovered a maximum total initial embodied energy consumption value of 1.66×10^5 GJ (166,000 GJ) and the minimum value of 8.53×10^4 (85,000 GJ) for Project 1. Any other combination of upper and lower bound limits per individual life cycle phase would result in values between the stated maximum and minimum. For instance, the term 'Up-Low-Low' (i.e. line 4 in the table) relates to the maximum material phase energy and minimum transportation and construction phase energy consumption values, which equated to a total initial embodied energy consumption value of 1.65×10^5 GJ (165,000 GJ). Notably due to the significance of the material phase energy, only minor differences existed across lines 1-4 within the table. Moreover, the table also highlights the difference between the maximum and minimum value (i.e. range) and the error values discovered per individual life cycle phase. Therefore, considering the degree of uncertainty throughout the rates and quantities applied, the total initial embodied energy consumption value for Project 1 was discovered as 1.26×10^5 GJ ±32% (i.e. 4.02×10^4 GJ). Furthermore, Figure 4.12 illustrates the change in the relative significance of each individual life cycle phase due to errors within the measured values. Evidently, material phase energy remained dominant throughout each possible combination of upper and lower bound limits, though the significance of construction phase energy varied between 0.6% and 2.2% of the total.

Table 4.25 Range of total initial embodied energy consumption values (GJ) per individual life cycle phase due to uncertainty (Project 1)

Upper and Lower Bound Limit Combinations (MAT-TRAN-CON)	Material Phase (GJ)	Transportation Phase (GJ)	Construction Phase (GJ)	Total Initial Embodied Energy (GJ)
[1] Up-Up-Up	1.63E+05	6.84E+02	1.90E+03	1.66E+05 (i.e. Max)
[2] Up-Low-Up	1.63E+05	3.52E+02	1.90E+03	1.65E+05
[3] Up-Up-Low	1.63E+05	6.84E+02	9.79E+02	1.65E+05
[4] Up-Low-Low	1.63E+05	3.52E+02	9.79E+02	1.65E+05
[5] Low-Up-Up	8.41E+04	6.84E+02	1.90E+03	8.67E+04
[6] Low-Low-Up	8.41E+04	3.52E+02	1.90E+03	8.63E+04
[7] Low-Up-Low	8.41E+04	6.84E+02	9.79E+02	8.57E+04
[8] Low-Low-Low	8.41E+04	3.52E+02	9.79E+02	8.54E+04 (i.e. Min)
Range[b]	7.91E+04	3.32E+02	9.21E+02	8.04E+04
Measured Value[c]	1.24E+05	5.18E+02	1.44E+03	1.26E+05
Error Value (±32%)[d]	3.96E+04	1.66E+02	4.61E+02	4.02E+04

[a] Combinations: potential maximum and minimum value per individual life cycle phase (material-transportation-construction); Up, upper bound limit (i.e. +32%); Low, lower bound limit (i.e. -32%).
[b] Range: Up-Up-Up values minus Low-Low-Low values (i.e. the maximum minus the minimum value).
[c] Measured Value: measured value from data captured within Project 1 (i.e. 0% error)
[d] Error Value: difference between the measured value and upper or lower bound limits (i.e. ±32% error derived from the quantities and rates).

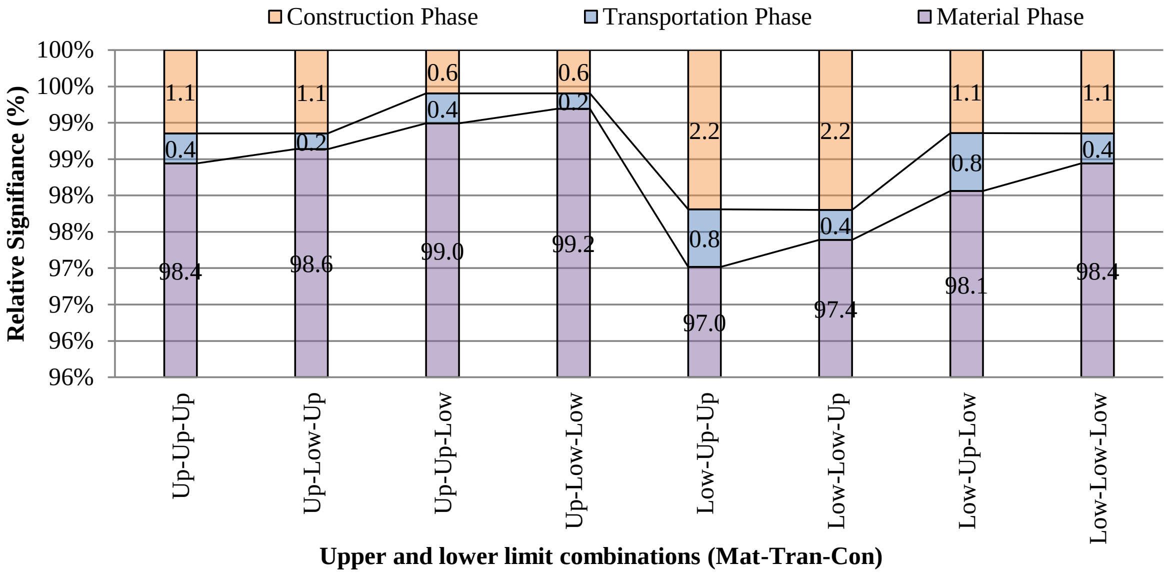


Figure 4.12 Comparison between the possible relative significance values (%) per individual life cycle phase due to uncertainty

Due to the complex nature of the construction project, certain data assumptions were necessary. It was assumed that only 80% of the total material scope within the groundworks, electrical, mechanical and refrigeration construction packages was captured due to issues regarding the type and number of materials included within the ICE material database, disparity within design drawings and BoQ's, and time constraints for managing data. The significance of the respective material phase impacts per construction package would have been greater than initially reported within Table 4.24. Hence, increasing the material phase impact for each previously identified construction package by an assumed value of 20%, resulted in an increased total initial embodied impact value of 0.8% (1,000 GJ) and 0.5% (89,000 kgCO_2e) for embodied energy and carbon respectively. Including the assumed data had no impact on the overall rankings of each construction package displayed previously in Table 4.24. Additional information on the data gaps and assumptions made by the RE is portrayed within paper 3 (Appendix C). The total initial embodied impact (energy and carbon) per individual life cycle phase is presented within Table 4.26 Evidently, material phase impacts were significantly greater than transportation and construction phase impacts. Thus to reduce initial embodied energy, project team efforts should be largely directed towards reducing material phase energy through improved selection of low-energy materials during design and efficient use of materials and effective waste reduction strategies on-site, as noted previously in literature (WRAP, 2015d; WRAP, 2015e).

Table 4.26 Total initial embodied impact per individual life cycle (after Davies et al., 2014, paper 3)

Life Cycle Phase	Embodied Energy (GJ) ±% error (± error value)	Sig (%)[a]	Embodied Carbon (kgCO_2e) ±% error (± error value)	Sig (%)[a]
Material Phase[b]	1.25E+05 ±32% (±3.99E+04)	98.5	1.75E+07 ±32% (±5.60E+06)	97.6
Transportation Phase	5.18E+02 ±32% (±1.66E+02)	0.4	3.53E+04 ±32% (±1.12E+04)	0.2
Construction Phase	1.44E+03 ±32% (±4.61E+02)	1.1	4.00E+05 ±32% (±1.280E+05)	2.2
Total	1.27E+05 ±32% (±4.05E+04)	100	1.79E+07 ±32% (±5.74E+06)	100

[a] Sig: relative significance (%) of each individual life cycle phase in relation to the total value.
[b] Material phase: total value includes the additional 20% assumed material phase values for the groundworks, electrical, mechanical and refrigeration construction packages.

Table 4.27 displays the estimated total waste consumption per material (i.e. waste stream) across each construction package within Project 1 derived from literature (section 3.2.3). Evidently, in terms of initial embodied energy, estimated waste consumption equated to 5.96 x10^4 GJ which corresponds to an additional 48% material phase energy. Including this estimated value within the total initial embodied energy consumption further highlights the importance of material and waste consumption with regards to addressing initial embodied energy consumption. In addition, the RE acknowledged material selection in general influenced transportation and construction phase impacts through changes in the type and number of project resources required. Therefore, despite the relative insignificance of transportation and construction phase energy within Project 1, the RE recognised from the contractor's perspective increased capture of transportation and construction phase data could further help confirm its significance and relationship between individual life cycle phases within future different project types, to discover potential hidden opportunities for reduced energy consumption. Furthermore, continued capture of the data in terms of construction packages could further help the contractor fulfil data requirements outlined within existing forms of environmental measurement (i.e. BREEAM) and help set targets and benchmark to drive reduced energy consumption. In addition, the RE recognised the contractor already undertakes a similar approach towards capturing data per construction package and sub-contractor to aid management of project cost and risk, which could be replicated to aid the awareness and application of cost and energy in future projects. Nonetheless, from the use of the practical framework within Project 1, the RE identified many challenges which inhibited the capture and assessment of data from the use of the current practices detailed within the framework. Table 4.28 illustrates these challenges and additional information beyond the evidence formerly presented in research cycle 2 (Table 4.17). The RE recognised overcoming these inherent challenges would result in improved data validity and reduce data gaps (e.g. transportation phase data) within following research cycles.

Table 4.27 Estimated volume of construction waste consumption and embodied impacts per material for Project 1

Construction Package (Sample)	Material (i.e. Waste Steam)	Volume (m^3)	EE (GJ)[a]	EC ($kgCO_2e$)[a]
Earthworks	Bricks (e.g. hardcore)	6.75E+01	3.89E+02	3.11E+04
Groundworks	Concrete (e.g. insitu, precast)	3.61E+02	8.40E+02	1.32E+05
Foundations	Inert (e.g. aggregate)	4.44E+02	2.98E+03	2.39E+05
External Walls	Insulation materials (e.g. cladding panels)	6.23E+01	8.02E+01	3.87E+03
Racking	Metals (e.g. steel tubes)	1.33E+02	2.55E+04	2.02E+06
All Packages	Packaging materials (e.g. wrapping)	2.01E+02	2.23E+04	9.18E+05
Syphonic Drainage	Plastic (e.g. HDPE pipe)	4.54E+01	3.70E+03	1.10E+05
All Packages	Timber (e.g. pallets)	2.90E+02	2.03E+03	0.00E+00
M&E	Electrical and electronic equipment (e.g. copper)	1.57E+00	4.41E+02	3.47E+04
Groundworks	Mixed construction & demolition (e.g. concrete)	5.68E+02	1.32E+03	2.07E+05
	Total Waste Consumption per Project	**2.17E+03**	**5.96E+04**	**3.70E+06**
	Waste Benchmark (m^3 per 100 m^2)[b]	1.11E+01		

[a] Totals: EE, embodied energy; EC, embodied carbon.
[b] Benchmark: Industry standard benchmark for project type (normalised per building area and included waste streams).

Table 4.28 Summary of challenges within contractor current practices (after Davies et al., 2014, paper 3)

Current Practices[a]	Findings
Programme of Works (PoW)	- PoW data obtained from the contractor's planner (not freely available); - PoW developed by the contractor was regarded as the target programme (Meikle and Hillebrandt, 1988); - No correlation between PoW and sequence of sub-contractor activities, thus RE had to verbally request this information from contractor operatives; - Contractor also developed multiple individual phasing and logistical plans for critical packages; - Sub-contractors created unique programmes which highlighted approximate construction resources per construction activity; - No consistency between the various forms of programmes used, activity ownership, duration or

	terminology.
Plant Register	- Register data obtained from the contractor's construction manager (not freely available); - Used to satisfy the requirements of the Provision and Use of Work Equipment Regulations 1998 (PUWER) (HSE, 2009); - Contractor captured information (i.e. plant description, serial number, and date of next inspection) from each sub-contractor when new items of plant and equipment arrived; - Information was captured within multiple sub-contractor specific registers; - No consistent terminology used to describe similar or even identical items of plant; - The level and type of information received was not organised or processed by the contractor beyond the original format.
EPI Procedure	- Procedure data obtained from the contractor's construction manager (not freely available); - Fuel consumption data (i.e. red diesel, petrol use) captured on monthly basis; - Contractor data was reviewed against hard copies of fuel delivery receipts and supported commercial and auditing purposes; - Sub-contractor data was not verified, compared or critically examined as they were not required to provide fuel delivery receipts; - Bowsers and large items of plant that were delivered to site already containing fuel (i.e. red diesel) were not considered; - Data was not pro-rata or measured at smaller intervals (weeks, days etc.) by the contractor or sub-contractors.
Sign-in Sheets	- Sheet data obtained from the contractor's office (freely available); - Two versions of sign-in sheets used; - Both versions containing the same name 'Contractors sign-in sheet' but different in terms of content; - One version sub-contractors were required to provide the following information: induction number, date, name, signature, company name, time in, and time out; - This version was thoroughly filled in by the operatives, whereby RE determined this was because the contractor used this sign-in sheet to address payments; - Other version site visitor was required to provide the following information: date, name, company, signature, time-in/out, transport type, fuel type, distance travelled, and onward travel distance; - This version contained scarce data entries with regards to transport type, fuel type, distance travelled, and onward travel distance.
Resource Database	- Database data obtained from the contractor's administrator (not freely available); - Occasionally sub-contractors maintained their own form of sign-in sheet; - This information was given to the contractor's administrator to input into the Resource Database; - Microsoft Access database designed to support the collection and assessment of project data in terms of resources such as the operative, plant, equipment, and materials; - Database was not fully maintained and only the contractor's administrator had sufficient knowledge of the database; - RE discovered there was no mandatory requirement to use the database.
SWMP	- Plan data obtained from the contractor's construction manager (not freely available); - Demonstrated project total waste consumption during the construction phase; - Information such as distance travelled, load capacity and form of transportation type was all captured; - Contractor initially employed the use of segregated skips (e.g. timber, metal, plastic, cardboard) for all sub-contractors to use, though method not maintained during the final stages; - RE identified that if segregated skips were maintained material waste and associated transportation impacts relative to specific construction packages, activities and sub-contractors could have been calculated to increase the granularity of the results.

[a] Current Practices: EPI, Environmental Performance Indicator Procedure; SWMP, Site Waste Management Plan.

4.6.1.4 Specified Learning

The third research cycle developed a practical framework for an initial embodied energy assessment from the exploration of secondary data within previous LCA studies and primary data from a live construction project. Twenty-six project indicators were considered within the existing LCA studies relative to different project life cycle phases, though transportation and construction phase impacts were frequently overlooked. Material phase energy was found to be significant, in particular within the ground and upper floor, external slab and frame construction packages, although difficulties emerged during the capture of transportation phase data from the live construction project. Furthermore, considering the overall effect changes uncertainty in measurement had on the relative significance of construction packages (e.g. the ground and upper floor package), the RE recognised the need for improved reliable quantities and rates to ensure data within future LCA studies truly reflects the salient features of a construction project. Hence, to improve the situation and the provision of future research, the RE identified the following advances: increased awareness of the relationship between individual project life cycle phases (including operational energy); enhanced current practices to capture detailed project data across construction packages, construction activities and sub-contractors relative to individual initial embodied energy phases (i.e. material, transportation and construction); and improved consideration towards the validation of captured project data.

4.6.2 Research Cycle 4 – Sub-objective 3.2

4.6.2.1 Diagnosing and Action Planning

To achieve sub-objective 3.2, the fourth research cycle explored the effectiveness of the practical framework to assess initial embodied energy consumption within UK non-domestic construction projects. Similar to the previous research cycle, the RE planned to undertake a critical review of literature (industry and contractor) and a case study accompanied by a quantitative analysis of primary data from a live construction project. In particular, the review of contractor literature was intended to develop the revised practical framework based upon the challenges identified from the previous research cycle (Table 4.28). Literature highlighted due to existing forms of environmental measurement (i.e. BREEAM), contractors are already expected to address primary and secondary data from construction projects with regards to each individual life cycle phase (i.e. material, transportation and construction) (Goggins et al., 2010; RICS, 2010; BREEAM, 2011; Monahan and Powell, 2011). Table 4.29 summarises context and leading questions that formed the basis of the research cycle, which concluded the fourth research paper presented in Appendix D.

Table 4.29 Research cycle 4 content and leading questions

Sub-Objectives[a]	Context	Leading Questions
3.2 Explore Practical Framework	The contractor is already expected to capture primary data for the transportation and construction phases, as well as secondary data for the material phase (Goggins et al., 2010; RICS, 2010; BREEAM, 2011; Monahan and Powell, 2011)	- What modifications can be made to the framework and contractor’s current practices to capture improved data? - Is their similarities between the relative significance of individual project life cycle phases (material, transportation, construction) for comparable project types?

[a] Sub-Objectives: MAT, Material life cycle phase; TRAN, Transportation life cycle phase; CON, Construction life cycle phase.

4.6.2.2 Action Taking

In line with the previous research cycle, a mixed methods approach was adopted to facilitate a multi-dimensional view on the subject, which stemmed from the previous review of industry literature (chapter 2) and existing procedure (section 3.2). In particular the RE built upon the findings derived from the previous research cycle and made changes to how data would be captured and assessed within the practical framework to improve its appropriateness in relation to the research objective. Figure 4.13 displays the relationship between the method type, explored data source and findings.

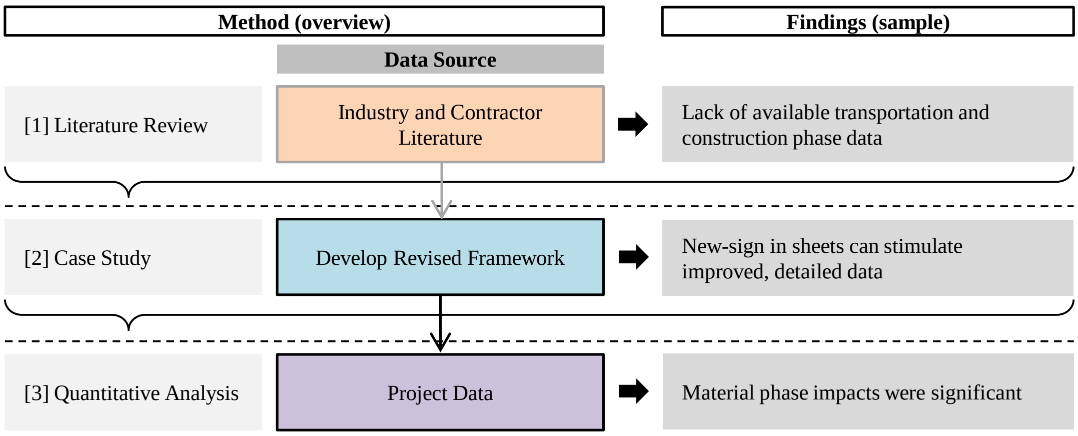


Figure 4.13 Relationship between the method and findings from the forth research cycle

Similar to the previous research cycle, the critical review of industry literature provided an industry perspective on existing LCA studies. In particular, the review derived from research papers (section 3.3) and aimed to highlight any gaps in knowledge or recent discoveries which may have been overlooked by the RE previously. This review updated the previous reviews presented within research cycle 2 and 3. Notably at this stage of the research project, the RE recognised many common limitations surrounding the use of existing data within previous LCA studies, such as: lack of clarity within previous studies surrounding adopted system boundaries, data sources and calculation methods; a lack of transportation and construction phase data across assorted project types; a lack of primary in-depth data (e.g. per construction package) from UK construction projects; and, with the expectation of some studies (e.g. Stephan et al., 2012), a lack of reference towards uncertainty within results. Hence, these limitations stimulated the actions undertaken within the remaining fourth research cycle.

The RE built upon the preceding review by undertaking a critical review of contractor literature to form a revised practical framework to support an initial embodied energy assessment. The revised framework, which was designed on the same data requirements (i.e. principles, indicators, structure, equations, and alignment) as the previous framework, intended to overcome the inherent challenges embedded within the existing contractor current practices noted within the previous research cycle (Table 4.28); though changes were made to the structure and alignment of contractor current practices. In particular, the RE reviewed the current practices used by the contractor during the construction phase of a UK non-domestic construction project (Project 2), whereby four current practices (i.e. plant register, EPI procedure, programme of works, and sign-in sheets) were further developed. The selection process and characteristics of the current practices and construction project was in line with the previous research cycle. Furthermore, due to the active involvement within the construction project, the RE determined a sample of construction packages which were investigated within the construction project (section 3.2).

The RE undertook a case study in the form of an observational technique and quantitative analysis which explored the effectiveness of the revised practical framework (derived from the previous review) within a live construction project. Actions undertaken within the case study were primarily aimed to overcome the limitations surrounding the use of existing data within previous LCA studies introduced previously (above). The effectiveness of the framework was determined with regards to the reliability (i.e. consistency and stability of data) and validity (i.e. appropriateness of the data) of data captured per project indicator. As previously highlighted within section 3.3, to aid data reliability, the RE employed the same non-intrusive participant observation technique, as presented within research cycle 3, to determine a detailed account of primary data from the contractor's actions and practices within the explored construction project (i.e. Project 2). Data was captured during different intervals throughout the construction phase of the project once to allow time to process data and not to interfere with the workings of the contractor. Multiple Microsoft Excel spreadsheets were used to assess the captured data in line with the methodology previously described in section 3.4.

4.6.2.3 Evaluating

From the review of industry literature, the RE acknowledged disparity regarding which project stakeholder (e.g. developer, client, designer, contractor, sub-contractor) was commonly deemed most appropriate to tackle initial embodied energy consumption and experience the associated risk and rewards (HM Treasury, 2013; RICS, 2012; UK-GBC, 2012). Building Information Modelling (BIM) has gained prominence within recent studies, as researchers suggested BIM could help project stakeholders address data requirements and reduce energy consumption within future projects through the creation and use of intelligent databases and 3D models (Vilkner et al., 2007; Goedert and Meadati, 2008; Mah et al., 2010; Wu et al., 2014). The RE acknowledged that BIM will most likely play an important role within the future of the research topic and provide functional support to project stakeholders during design and construction phases. Despite not being truly considered and deemed beyond the scope of the research project, the RE recognised value in comprehending how the developed framework could be aligned with the requirements of BIM related projects to support within future studies surrounding initial embodied energy consumption. Details of the review are presented in paper 4 (Appendix D) and section 2.5.1. A summary of the key findings are summarised in Table 4.30.

Table 4.30 Findings from the review of industry literature (after Davies et al., 2015, paper 4)

Focus	Review of Industry Literature Findings
Project life cycle energy	- Building Information Modelling (BIM) can help project stakeholders capture and assess data in the future to identify opportunities to reduce energy consumption through intelligent databases and 3D models (Vilkner et al., 2007; Goedert and Meadati, 2008; Mah et al., 2010; Wu et al., 2014);
Material phase data	- Many previous studies have emphasised the importance of building frame and envelop design in order to help reduce initial embodied energy consumption (Suzuki et al., 1995; Cole and Kernan, 1996; Kofoworola and Gheewala, 2009; Rai et al., 2011; Van Ooteghem and Xu, 2012; Han et al., 2013).
Transportation phase data	- There is a common view within literature that reducing this impact will not result in significant energy reductions for a project or wider industry (Hamilton-MacLaren et al., 2009; RICS, 2012).
Construction phase data	- Currently there is a lack of accurate data within literature which reflects the impact of the construction phase across various projects, especially as significant time, money and effort are required to capture and assess this data (Hamilton-MacLaren et al., 2009; Janssen, 2014).

From the review of contractor literature and findings from the previous research cycle, four current practices (i.e. plant register, EPI procedure, programme of works, and sign-in sheets) were altered by the RE and explored within Project 2. The challenges and corresponding changes made to the existing contractor current practices are summarised within Table 4.31. Further detail surrounding the development of the alternative current practices is detailed within paper 4 (Appendix D) though key changes are summarised below.

Table 4.31 Changes to contractor current practices to support the revised framework (after Davies et al., 2015, paper 4)

Current Practice	Existing Challenges	Changes (made of overcome challenges)
Programme of Works (PoW)	No direct link between construction activities and sub-contractors. Limit use to link data from all other current practices needed to support detailed benchmarks and identify salient issues (i.e. hot spots) with regards to data and consumption.	**[No.1]** Develop a PoW which clearly highlights which sub-contractors are responsible for each construction package and activity to act as a basis to support all other current practices.
Plant Register	Information varied in terms of content, detail, legibility and terminology. Limit use to relate specific items of plant and equipment to construction packages.	**[No.2]** Develop a single register to collect all plant and equipment data from sub-contractors. Format the single register to identify missing or unclear information relating to known plant and equipment types.
On-site Energy Management Procedure	Unclear information surrounding fuel data in terms of quantity of delivery, the date of delivery, and consumption during intervals. Limit information on how, where or why fuel was consumed on-site in relation to construction packages.	**[No.3]** Develop a pro forma which requires sub-contractors to provide weekly fuel usage data. Format the pro forma and provide clear instruction defining the need for fuel delivery tickets to be accompanied with all data submissions. **[No.4]** Develop check-sheets which track data submission made by sub-contractors in terms of frequency and detail. Format the check-sheets to highlight outstanding sub-contractor data. Link the data to construction package durations (high-level) to recognise when sub-contractor data will be available and finish.
Sign-in Sheets	Lack of transportation data (e.g. mode, distance, frequency) captured due to site set-up and poor management of current practice at site entrance. Limit use to produce detailed data and links to specific construction packages.	**[No.5]** Develop a new sign-in sheet which links material, plant and equipment deliveries (and collections) to specific sub-contractors. **[No.6]** Develop a new sign-in sheet which links operative movements (to and from site) to specific sub-contractors. **[No.7]** Develop a new sign-in sheet which links on-site plant and equipment use to specific construction packages and activities.

As noted previously (above), the revised framework was designed on the same basis as the previous framework (research cycle 3) though changes were made to the structure and alignment of contractor current practices. Table 4.32 displays the alignment of current practices (existing and changed) to project indicators per individual life cycle across both research cycles 3 and 4. Evidently alterations were only made to the capture of transportation and construction phase data, as the RE deemed the existing current practices (i.e. bill of quantities and design drawings) were appropriate to provide the necessary material data. Figure 4.14 illustrates the structure of the revised framework in relation to the developed three new sign-in sheets (Forms 'A', 'B' and 'C'). Form 'A' captured material, plant and equipment transportation data, whereas Form 'B' captured operative transportation data. Form 'C' captured construction phase data in terms of the number and type of operatives, plant and equipment per construction activity.

Table 4.32 Alignment of current practices to project indicators per life cycle (after Davies et al., 2015, paper 4)

Life Cycle Phase	Project Resources	Project Indicators (Embodied Energy)	Units	Research Cycle 3 Current Practices[a]	Research Cycle 4 Current Practices[a]
MAT	Material	Characteristics	type, no., m2, m3, tonne	BoQ, Drawings	BoQ, Drawings
TRAN	Material	Distance travelled	miles, km	Sign-in sheet, SWMP	Form 'A'
		Vehicle used	type, no.	Sign-in sheet, SWMP	Form 'A'
		Vehicle fuel used	petrol, diesel etc.	Sign-in sheet, SWMP	Form 'A'
		Vehicle fuel consumption	litres, kWh	Sign-in sheet, SWMP	Form 'A'
		Vehicle load capacity	tonne, m^3	Sign-in sheet, SWMP	Form 'A'
		Proportion of load	%	Sign-in sheet, SWMP	Form 'A'
	Plant and Equipment	Distance travelled	miles, km	Sign-in sheet, SWMP	Form 'A'
		Vehicle used	type, no.	Sign-in sheet, SWMP	Form 'A'
		Vehicle fuel used	petrol, diesel etc.	Sign-in sheet, SWMP	Form 'A'
		Vehicle fuel consumption	litres, kWh	Sign-in sheet, SWMP	Form 'A'
		Vehicle load capacity	tonne, m^3	Sign-in sheet, SWMP	Form 'A'
		Proportion of load	%	Sign-in sheet, SWMP	Form 'A'
	Operatives	Distance travelled	miles, km	Sign-in sheet	Form 'B'
		Vehicle used	type, no.	Sign-in sheet	Form 'B'
		Vehicle fuel used	petrol, diesel etc.	Sign-in sheet	Form 'B'
		Vehicle fuel consumption	litres, kWh	Sign-in sheet	Form 'B'
		Vehicle load capacity	tonne, m^3	Sign-in sheet	Form 'B'
		Proportion of load	%	Sign-in sheet	Form 'B'
CON	Material + Plant and Equipment +	Material needed	type, no.	Resource, BoQ, PoW	Res', BoQ, PoW
		Operatives needed	type, no.	Resource, PoW	Form 'C', Res', PoW
		Plant needed	type, no.	Plant register, PoW	Form 'C', Plan, PoW
		Plant duration of use	hrs, days	Plant register, PoW	Plant register, PoW

Operatives	Plant fuel type	petrol, diesel etc.	Plant register, EPI	Plant register, EPI
	Plant fuel consumed	litres, kWh	Plant register, EPI	Plant register, EPI
	Plant power rating	v, a, watts	Plant register	Plant register

[a] Contractors current practices (i.e. data sources): Form 'A','B','C', New Sign-in Sheets; PoW, Programme of Works; BoQ, Bill of Quantities; Plan, Plant Register; Res', Resource Database; EPI, On-site Energy Management Procedure (i.e. EPI Procedure).

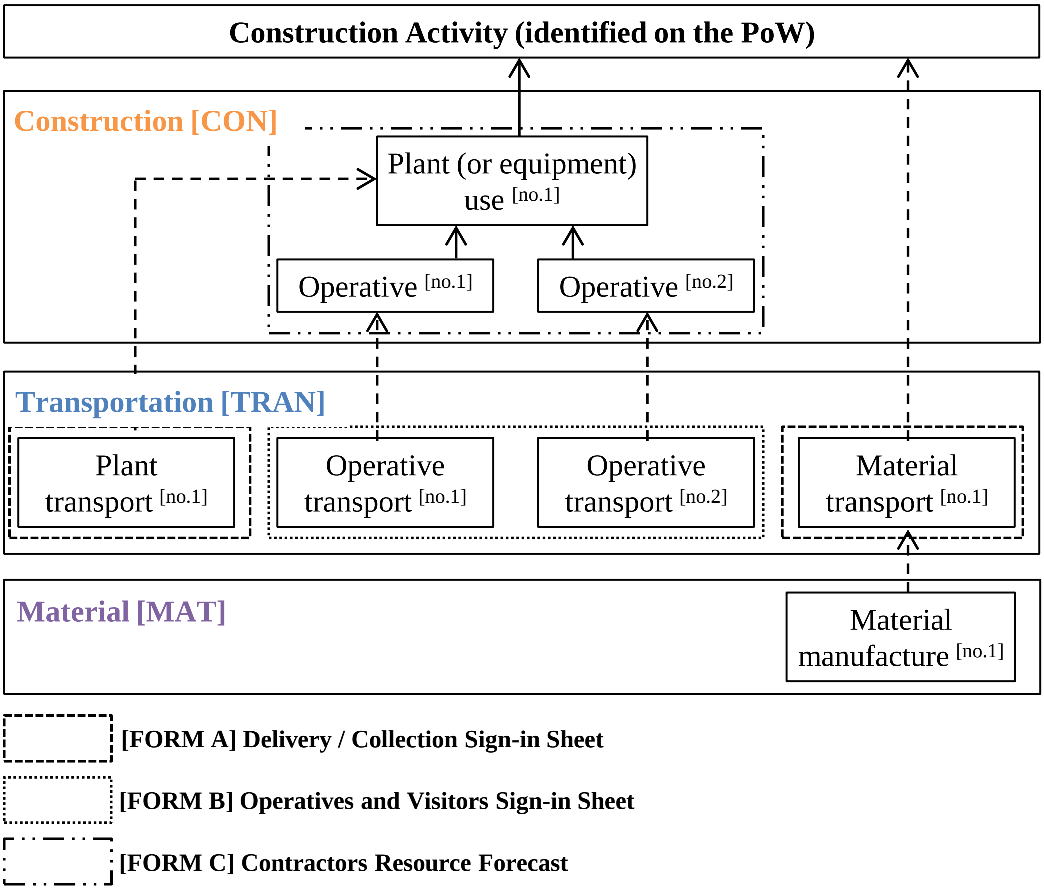


Figure 4.14 Structure of the revised framework in relation to the new sign-in sheets (after Davies et al., 2014, paper 4)

Table 4.33 presents a comparison between the existing approach and alternative approach for EPI procedure use. Section 3.3 highlighted the steps undertaken by the RE to implement the alternative approach. Adopting the changes identified in Table 4.31 enabled the RE to capture detailed weekly construction phase data (i.e. fuel consumption) per construction package as illustrated in Figure 4.15. The changes improved the granularity of data and overall effectiveness of the current practice by facilitating complete and appropriate data which could be verified by the accompanied delivery notes (provided by sub-contractors).

Table 4.33 Comparison between the EPI approach for Research Cycles 3 and 4

Criteria	Existing Approach (Research Cycle 3)	Alternative Approach (Research Cycle 4)
Timescale for capturing data	Monthly	Weekly
Data capturing methods	Sub-contractors email data Contractor personal correspondence	Sub-contractors email pro forma data Contractor personal correspondence Sub-contractors provide hard copies of data
Mechanisms for verifying data	COINS database	COINS database Check-sheet 1 – fuel delivery tickets Check-sheet 2 – quality of responses Improved PoW (change no.1)

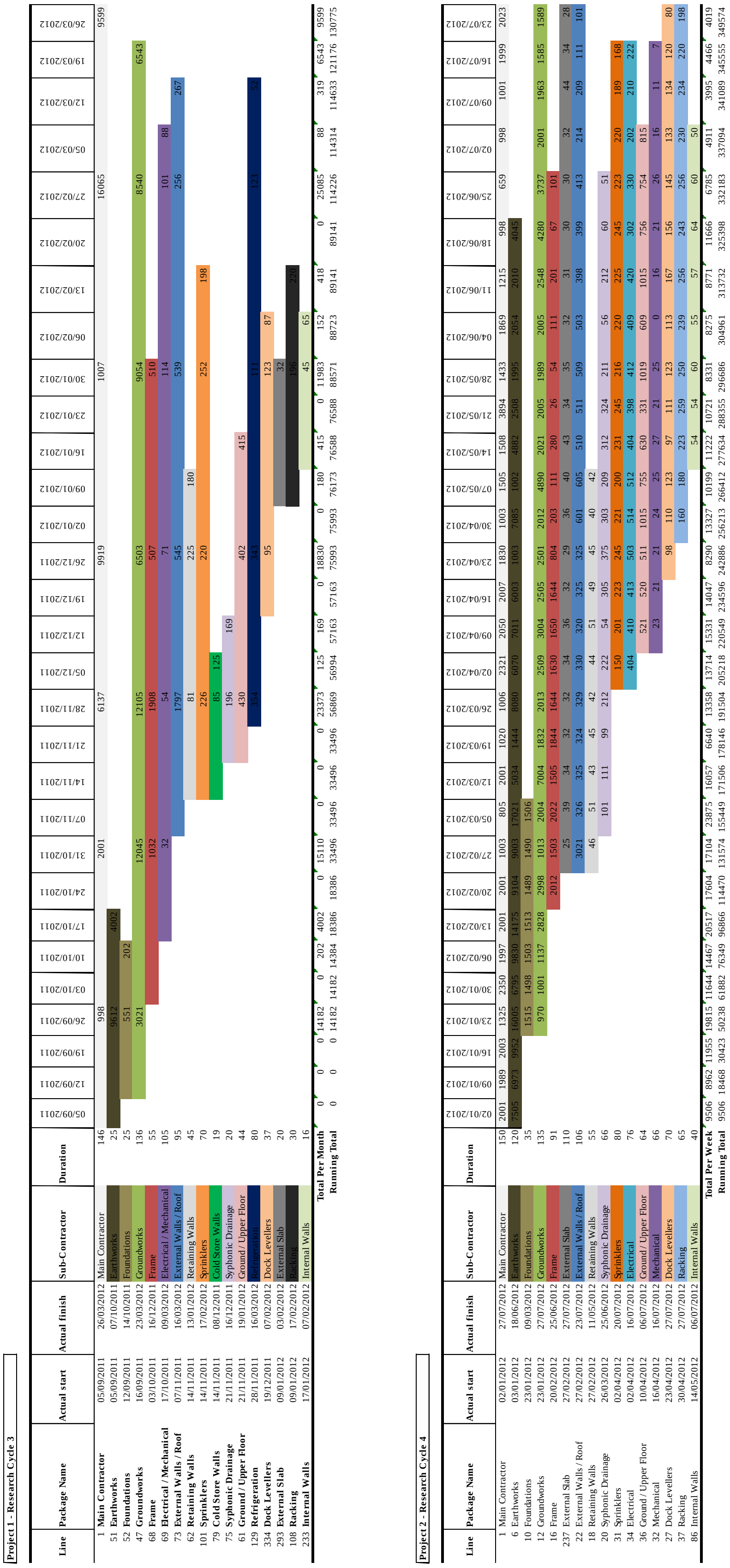


Figure 4.15 Comparison between the construction phase data (i.e. red diesel) captured from Project 1 and 2

To determine the overall effectiveness of the framework during its use within Project 2, the RE firstly explored the reporting scope (i.e. system boundaries) of the case study. In this instance the reporting scope was defined as the sample of data captured per category (e.g. construction package) in relation to the total population of data available. Table 4.34 compares to the difference between the total population of data and sample data within the case study. Evidently, 38% of construction packages which were explored by the RE represented 81% of total project turnover. In this instance, the term 'turnover' referred to project value and was traditionally used by the contractor to normalise project data. This value was important to note as the RE estimated that increased procurement and use of project resources (i.e. materials, plant and equipment, and operatives) would drive increased energy consumption per individual life cycle phase (e.g. manufacture, transport and install new material) which would be reflected within the turnover. As a result, the following construction packages which corresponded to the remaining 62% not considered within the study were as follows (selected examples): staircases, soft landscaping, ceramic tiling, joinery, bricklaying, decorating and furniture, tarmacadam, line markings, and professional services (e.g. commissioning, air pressure testing, fire protection). The RE recognised that including these construction packages within the study would increase the reported embodied energy consumption values (see below) though the impact on the overall findings would have been small. For example, despite bricks being more energy intensive (3.00 MJ/kg) to manufacture than the pre-cast concrete (1.46 MJ/kg) used to form the retaining wall, due to the estimated small volume of material used (1.42 m^3), including this embodied impact (8.00 GJ) would have had minor consequences on the overall findings. Furthermore, with regards to the new sign-in sheets, Forms 'A', 'B' and 'C' captured approximately 92%, 64% and 38% of the total project data available respectively, with 81%, 69% and 53% of the responses deemed fully complete respectively (Table 4.35). Absent data and discrepancies within the sign-in sheets were addressed by the RE through interaction with the respective sub-contractor management and operatives.

Data from the construction packages outside the reporting scope was also captured within the sign-in sheets, though this data was not thoroughly evaluated (i.e. organised, calculated and validated) by the RE. From reviewing the findings, the RE recognised that despite only 38% of the total construction packages available were investigated, these construction packages were responsible for 92% of all material and plant and equipment movements throughout the total population of data. Hence the remaining 8% of material and plant and equipment transportation movements corresponded to the 62% of construction packages not considered within the study. However, in terms of operative movements, the explored construction packages only corresponded to 64% of the total population of data. As previously introduced in section 3.3, despite efforts made to improve the reliability and validity of the captured data, the RE was occasionally still required to request additional clarification of data from sub-contractor operatives and management when data was incomplete. Consideration of the reporting scope and completeness of data enabled the RE to comprehend the degree of uncertainty within the capture data and assess the effectiveness of the current practices and revised framework towards providing a true representation of total initial embodied energy consumption for Project 2. More information on the reporting scope and the level and type of responses received is highlighted below and detailed within paper 4 (Appendix D).

Table 4.34 Reporting scope of the case study within Project 2

Scope	**Activities**		**Packages**		**Sub-contractors**		**Turnover**	
	No. [a]	**%** [b]	**No.** [a]	**%** [b]	**No.** [a]	**%** [b]	**Total** [a]	**%** [b]
Total Project Data (i.e. population data)	243	100	40	100	31	100	2.69E+07	100
Reporting Scope[c] (i.e. sample data)	101	42	15	38	15	48	2.19E+07	81
Non-reporting Scope[d] (i.e. non-sample)	142	58	25	62	16	52	4.98E+06	19

[a] No.; total number (or value) of construction activities, packages, sub-contractors, and turnover.
[b] Percentage; total number (or value) of construction activities, packages, sub-contractors, and turnover as a percentage of total project data.
[c] Reporting scope; investigated number (or value) of construction activities, packages, sub-contractors, and turnover.
[d] Non-reporting scope; non-investigated number (or value) of construction activities, packages, sub-contractors, and turnover.

Table 4.35 Response rate and reporting scope per new sign-in sheet

Sub-contractor Name	Form 'A'			Form 'B'		Form 'C'	
	MAT	PLANT	Total[a]	OPS	Total[b]	CON	Total[c]
Main Contractor	0	239	239	1,480	1,480	-	-
Earthworks	0	43	43	887	887	1	1
Foundations	82	7	89	119	119	1	1
Groundworks	299	44	343	4,473	4,473	1	1
Frame	95	33	128	189	189	1	1
External Slab	2,561	6	2,567	1,193	1,193	1	1
External Walls / Roof	357	22	379	1,458	1,458	1	1
Retaining Walls	24	6	30	108	108	1	1
Syphonic Drainage	30	8	38	199	199	1	1
Sprinklers	118	17	135	581	581	1	1
Electrical	14	22	36	622	622	1	1
Ground / Upper Floor	2,149	22	2,171	696	696	1	1
Mechanical	48	12	60	498	498	1	1
Dock Levellers	52	11	63	589	589	1	1
Racking	132	15	147	1,810	1,810	1	1
Internal Walls	14	6	20	222	222	1	1
Total sub-contractor data entries[d]	**5,975**	**513**	**6,488**	**15,124**	**15,124**	**15**	**15**
Total project data entries[e]			**7,020**		**23,670**		**40**
Difference[f]			**532**		**8,546**		**25**
Reporting scope (%)[g]			**92**		**64**		**38**
Non-reporting scope (%)			**8**		**36**		**62**
Complete data entries (%)[h]			**81**		**69**		**53**
Non-complete data entries (%)			**19**		**31**		**47**

[a] Total; total number of material (MAT) and plant and equipment (PLANT) data entries captured by Form 'A'.
[b] Total; total number of operative (OPS) data entries captured by Form 'B'.
[c] Total; total number of sub-contractor construction data entries captured by Form 'C'.
[d] Total sub-contractor data entries; total number of sub-contractor data entries within the reporting scope.
[e] Total project data entries; total number of sub-contractor data entries across reporting scope and non-reporting scope.
[f] Difference; difference between total project data entries and investigated sub-contractor data entries per Form.
[g] Reporting scope; total number of investigated sub-contractor data entries as a percentage per Form.
[h] Responses; total number of complete investigated sub-contractor data entries as a percentage per Form.

From the use of the revised practical framework within Project 2, in terms of the material phase, the RE discovered the insulated cladding panels included within the external walls and roof construction package were the most energy intensive materials to manufacture (101.5 MJ/kg). Diversity was identified within the embodied energy and carbon consumption findings across the construction packages. In terms of embodied energy, the most significant construction packages were the ground and upper floors (i.e. in-situ concrete slab) (44%), external slab (i.e. in-situ concrete slab) (13%) and frame (i.e. steel columns and beams)

(13%). Though, in relation to embodied carbon, the same construction packages were responsible for 21%, 54% and 7% of the total respectively. The change in ranking between ground and upper floor and external slab construction package was due to differences within the material rates within the ICE material database. The concrete used within the external slab construction package consisted of traditional in-situ concrete (RC 32/40 with 15% fly ash cement replacement) with steel reinforcement bars (110kg/m^3) which was less energy intensive (2.1 MJ/kg) (BSRIA, 2011) to produce than steel fibre-reinforcement concrete (7.8 MJ/kg) (BSRIA, 2011) used within the ground and upper floor construction package. Considering the findings, despite literature highlighting the terms embodied energy and carbon as interlinked (Dakwale et al., 2011; Dixit et al., 2012), the RE recognised the need to establish which environmental topic should be the main focus within future research and action undertaken by project stakeholders to drive reduced environmental impacts during construction.

Interestingly, during the initial phase on-site the contractor reprocessed the remaining in-situ concrete ground floor slab, ground beams and foundations from the demolition works which occurred before the contractor's tenure. Approximately 55,000 m^3 of aggregate material was reprocessed during this stage. Evidently, the decision to reprocess and form aggregates on-site enabled certain material transportation impacts to be offset by additional construction impacts as on-site fuel use primarily related to the reprocessing and transformation of the demolition into useable aggregates. In terms of material phase energy, the RE estimated the use of recycled aggregate saved 6.16×10^3 GJ (50%) of energy in comparison to virgin aggregate.

The RE discovered material, plant and equipment, and operative transportation impacts were responsible for 64%, 5% and 31% of the total transportation phase impact respectively. Figure 4.16 displays the relative significance of the different transportation impacts for each project resource per construction package against the total impact. In terms of material transportation, the external walls and roof, racking (i.e. steel racking), and frame construction packages were the most significant; representing 37%, 12% and 9% of the total respectively. The contractor was responsible for the most plant and equipment transportation impacts (22%) as 198 of their 239 movements related to transfer of construction waste (2,200 m^3) to a local recycling facility which was located approximately 16 km from site. The RE discovered a total of 15,100 operative movements occurred, equating to a distance of 832,000 km to and from site. Figure 4.16 displays the relative significance of the different transportation impacts for each project resource per construction package. Evidently material phase transportation was significant for the foundations construction package. The RE discovered this was due to the following reasons: 82 material deliveries of pre-cast concrete piles from a distance of 180 km from site were required; only two deliveries of plant (i.e. piling rig and fuel bowser) were required, of which remained on-site for the duration of the package; and only seven operatives were required, which were based locally (i.e. less than 10 km from site). These findings reiterate the existing views in literature (BRE, 2003; Citherlet and Defaux, 2007; Ko, 2010) regarding the importance of locally sourced project resources to minimise transportation phase impacts. Furthermore, in terms of the construction phase, the earthworks, groundworks and contractor were the most significant construction packages and responsible for 47%, 19% and 14% of the total respectively. Further detail of the findings relative to each initial embodied energy phase is provided within paper 4 (Appendix D).

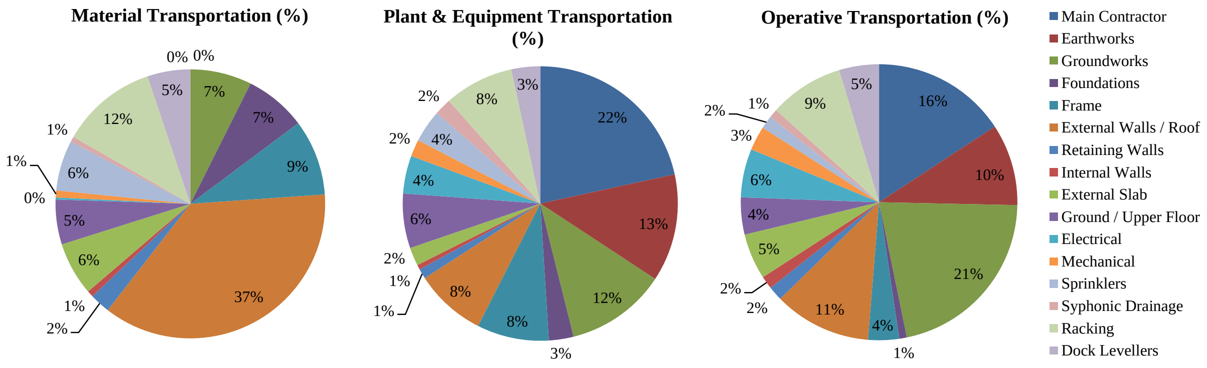


Figure 4.16 Comparison between the relative significance (%) of different transportation impacts per construction package against the total impact

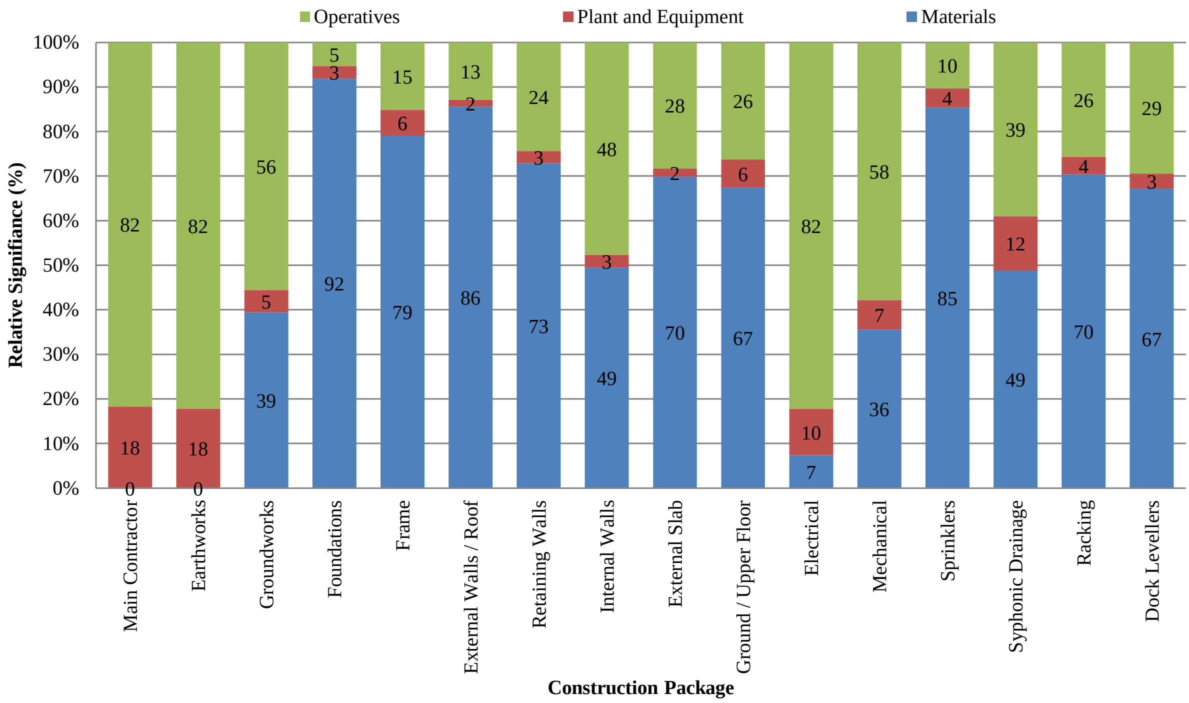


Figure 4.17 Comparison between the relative significance (%) of different transportation impacts per construction package

Table 4.36 summarises the total measured values discovered by the RE and the associated uncertainty (i.e. measurement error) in relation to the lower and upper bound limits for each individual life cycle phase. Table 4.37 displays the ranking of each construction package (in terms of significance) per individual life cycle phase, whereby the ranking of the most significant construction packages overall have been highlighted. Evidently the ranking of each construction package varied across each individual life cycle phase. The RE recognised, in the vast majority of cases, a positive relationship between the overall and material phase rankings per construction package.

Table 4.36 Total initial embodied energy consumption per construction package (Project 2)

Construction Package	Material Phase	Transportation Phase			Construction Phase	Total	Overall Rank
		Materials	Plant and Equipment	Operatives			
Gro & Upper Floor	2.44E+05	5.08E+02	4.79E+01	1.98E+02	4.89E+02	2.45E+05	1st
External Slab	7.45E+04	6.05E+02	1.60E+01	2.45E+02	4.45E+01	7.54E+04	2nd
Frame	7.17E+04	8.60E+02	6.30E+01	1.65E+02	6.82E+02	7.35E+04	3rd
Ext' Walls & Roof	4.96E+04	3.45E+03	6.24E+01	5.20E+02	4.19E+02	5.40E+04	4th
Racking	3.81E+04	1.09E+03	6.08E+01	3.98E+02	1.15E+02	3.98E+04	5th
Dock Levellers	3.38E+04	4.85E+02	2.52E+01	2.13E+02	6.70E+01	3.46E+04	6th
Groundworks	1.36E+04	6.95E+02	8.82E+01	9.80E+02	2.58E+03	1.79E+04	7th
Foundations	1.23E+04	6.96E+02	2.16E+01	4.04E+01	4.12E+02	1.35E+04	8th
Earthworks	6.16E+03	0.00E+00	9.44E+01	4.37E+02	6.52E+03	1.32E+04	9th
Electrical	6.51E+03	2.31E+01	3.31E+01	2.60E+02	2.37E+02	7.07E+03	10th
Sprinklers	5.01E+03	5.71E+02	2.86E+01	6.88E+01	1.34E+02	5.81E+03	11th
Main Contractor	0.00E+00	0.00E+00	1.61E+02	7.20E+02	1.95E+03	2.83E+03	12th
Mechanical	1.75E+03	7.93E+01	1.49E+01	1.29E+02	1.85E+01	2.00E+03	13th
Retaining Walls	1.63E+03	2.31E+02	8.73E+00	7.73E+01	1.95E+01	1.97E+03	14th
Internal Walls	3.32E+02	7.13E+01	4.23E+00	6.88E+01	1.78E+01	4.94E+02	15th
Syphonic Drainage	4.56E+01	5.94E+01	1.48E+01	4.74E+01	1.57E+02	3.25E+02	16th
Totals (Measured)[a]	5.59E+05	9.42E+03	7.45E+02	4.57E+03	1.39E+04	5.87E+05	
Tot' (Lower Limit)[a]	3.80E+05	6.41E+03	5.06E+02	3.11E+03	9.43E+03	3.99E+05	
Tot' (Upper Limit)[a]	7.37E+05	1.24E+04	9.83E+02	6.03E+03	1.83E+04	7.75E+05	

[a] Totals: Measured, measured value discovered from Project 1 data (i.e. table data); Lower Limit, lowest possible value (i.e. -32%); Upper Limit, highest possible value (i.e. +32%).

Table 4.37 Construction package ranking per individual life cycle phase (Project 2)

Rank	Material Phase[a]	Transportation Phase[a]			Construction Phase
		Materials	Plant and Equipment	Operatives	
1st	Gro' & Up' Floor	Ex' Walls & Roof	Main Contractor	Groundworks	Earthworks
2nd	External Slab	Racking	Earthworks	Main Contractor	Groundworks
3rd	Frame	Frame	Groundworks	Ex' Walls & Roof	Main Contractor
4th	Ex' Walls & Roof	Foundations	Frame	Earthworks	Frame
5th	Racking	Groundworks	Ex' Walls & Roof	Racking	Gro' & Up' Floor
6th	Dock Levellers	External Slab	Racking	Electrical	Ex' Walls & Roof
7th	Groundworks	Sprinklers	Gro' & Up' Floor	External Slab	Foundations
8th	Foundations	Gro' & Up' Floor	Electrical	Dock Levellers	Electrical
9th	Electrical	Dock Levellers	Sprinklers	Gro' & Up' Floor	Syphonic Drainage
10th	Earthworks	Retaining Walls	Dock Levellers	Frame	Sprinklers
11th	Sprinklers	Mechanical	Foundations	Mechanical	Racking
12th	Mechanical	Internal Walls	External Slab	Retaining Walls	Dock Levellers
13th	Retaining Walls	Syphonic Drainage	Mechanical	Internal Walls	External Slab
14th	Internal Walls	Electrical	Syphonic Drainage	Sprinklers	Retaining Walls
15th	Syphonic Drainage	Earthworks	Retaining Walls	Syphonic Drainage	Mechanical
16th	Main Contractor	Main Contractor	Internal Walls	Foundations	Internal Walls

[a] Values: highlighted the three most significant construction packages to show change in ranking per individual life cycle phase.

Table 4.38 displays the range of total initial embodied energy consumption values per individual life cycle phase due to errors within the measured values (i.e. quantities and rates). Considering the upper and lower bound limits (i.e. +32% and -32% respectively), the RE discovered a maximum total initial embodied energy consumption value of 7.75×10^5 GJ (775,000 GJ) and the minimum value of 3.99×10^5 (399,000 GJ) for Project 2. Note to simplify the calculation, individual transportation phase impacts per project resource were combined to form a single total upper bound limit and lower bound limit. Figure 4.18 illustrates the change in the relative significance of each individual life cycle phase due to errors within the measured values. Evidently, due to the upper and lower bound limits the significance of transportation phase energy varied between 4.8% and 1.3% of the total respectively.

Table 4.38 Range of total initial embodied energy consumption values (GJ) per individual life cycle phase due to uncertainty (Project 2)

Upper and Lower Bound Limit Combinations (MAT-TRAN-CON)	Material Phase (GJ)	Transportation Phase (GJ)	Construction Phase (GJ)	Total Initial Embodied Energy (GJ)
[1] Up-Up-Up	7.37E+05	1.94E+04	1.83E+04	7.75E+05 (i.e. Max)
[2] Up-Up-Low	7.37E+05	1.00E+04	1.83E+04	7.66E+05
[3] Up-Low-Up	7.37E+05	1.94E+04	9.43E+03	7.66E+05
[4] Up-Low-Low	7.37E+05	1.00E+04	9.43E+03	7.57E+05
[5] Low-Up-Up	3.80E+05	1.94E+04	1.83E+04	4.18E+05
[6] Low-Up-Low	3.80E+05	1.00E+04	1.83E+04	4.08E+05
[7] Low-Low-Up	3.80E+05	1.94E+04	9.43E+03	4.09E+05
[8] Low-Low-Low	3.80E+05	1.00E+04	9.43E+03	3.99E+05 (i.e. Min)
Range[b]	3.58E+05	9.43E+03	8.88E+03	3.76E+05
Measured Value[c]	5.59E+05	1.47E+04	1.39E+04	5.87E+05
Error Value (±32%)[d]	1.79E+05	4.72E+03	4.44E+03	1.88E+05

[a] Combinations: potential maximum and minimum value per individual life cycle phase (material-transportation-construction); Up, upper bound limit (i.e. -32%); Low, lower bound limit (i.e. +32%).
[b] Range: Up-Up-Up values minus Low-Low-Low values (i.e. the maximum minus the minimum value).
[c] Measured Value: measured value from data captured within Project 1 (i.e. 0% error)
[d] Error Value: difference between the measured value and upper or lower bound limits (i.e. ±32% error derived from the quantities and rates).

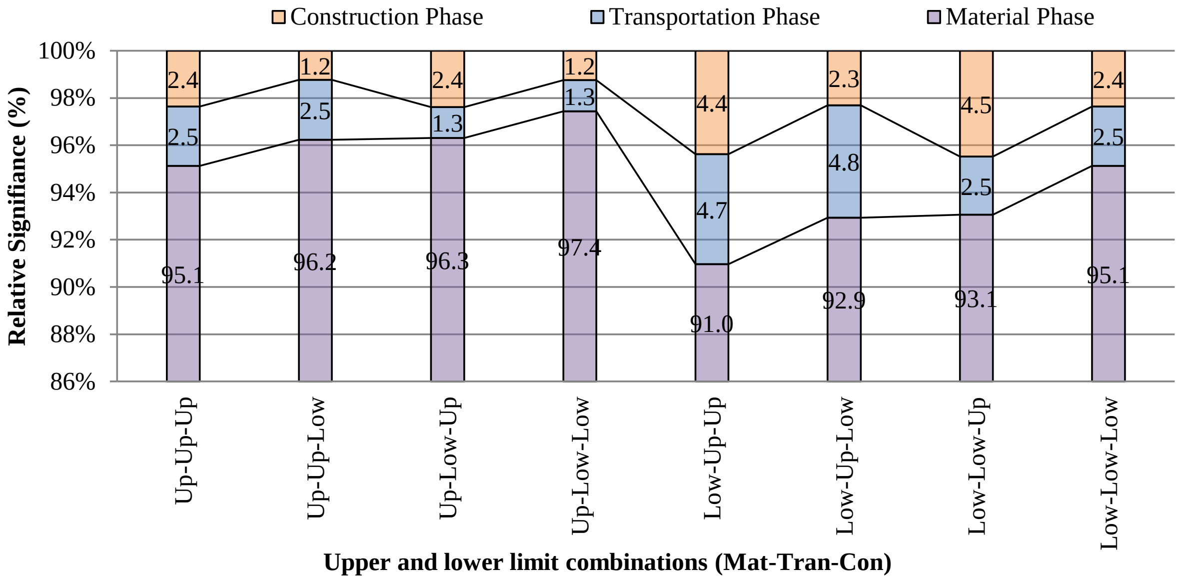


Figure 4.18 Comparison between the possible relative significance values (%) per individual life cycle phase due to uncertainty (Project 2)

Despite efforts to limit data assumptions during the use of the revised framework, certain assumptions were deemed necessary by the RE to overcome gaps in data identified during the capture and processing of data. Consideration towards theses gaps in data helped the RE put the overall findings derived from the revised framework into context, in terms of data reliability and validity. It was assumed that only 80% of total material phase data was captured within the groundworks, electrical and mechanical construction packages. Hence to accommodate this assumption, the material phase impacts for the respective construction packages were increased by 20%. Furthermore, Table 4.39 displays a comparison between the reporting scope and non-reporting scope within Project 2. In particular, the first column summaries the percentage of measured values per life cycle phase captured within the reporting scope based upon the explored current packages. For example, the RE calculated that 81% and 26% of the total population of material and construction phase data available respectively was embedded within the 15 explored construction packages. The second column displays the non-reporting scope which reflects data not captured by the RE (i.e. data gaps). Therefore, to accommodate for these gaps in data, the RE estimated the non-reporting scope to be responsible for an additional 3% of total initial embodied energy consumption. This figure was derived from the RE's professional judgement and review of construction packages, and corresponding materials, within the contractor current practices (e.g. PoW, BoQ, design drawings). As noted previously, despite some of the packages containing energy intensive materials (e.g. bricks, steel, ceramic tiles) due to the small volume of material expected to be used within the project, their significance was estimated to be small. To put into context, seven of the explored construction packages (i.e. main contractor, retaining wall, internal walls, electrical, mechanical, sprinklers, and syphonic drainage) equated to approximately 4% of total initial embodied energy consumption.

Table 4.39 Comparison between the reporting scope (i.e. measured values) and non-reporting scope (i.e. data gaps) for Project 2

Life Cycle Phase Data[a]	Reporting Scope (i.e. sample data) (% of total data available)	Non-reporting Scope (i.e. non-sample) (% of total data available)
No. of Construction Packages	**15 (38%)**	**25 (62%)**
Material Phase Data	81%	19%
Transportation Phase – Material Data	92%	8%
Transportation Phase – Plant Data	92%	8%
Transportation Phase – Operatives Data	64%	36%
Construction Phase Data	26%	74%
% of Total Population of Data	97% of total	3% of total

[a] Life Cycle Phase Data: Construction Packages, obtained from a review of the PoW; Material Phase Data, assumed to be liked to Project Turnover (see Table 4.34); Transportation Phase, obtained from sign-in sheet data; Construction Phase, obtained from sign-in sheet and EPI Procedure data.
[b] % Total: values within the reporting scope estimated to represent 97% of total whereas values within non-reporting scope estimated to represent 3% of total.

Table 4.40 displays the total initial embodied impact (energy and carbon) per individual life cycle phase, including consideration towards all previous assumptions and gaps in data. Evidently, the material phase impact was responsible for 95.2% and 97.0% of the total initial embodied energy and carbon respectively; with construction packages predominately containing steel and concrete-based materials (i.e. ground and upper floor, external slab and frame) being most significant. The RE recognised that reduced material phase energy could be derived from project teams selecting alternative lower embodied impact materials within these packages, although material quantities, characteristics and performance criteria would need to be considered. Changes in material selection could result in changes to on-site construction techniques, procurement methods, operational energy efficiency, architectural form, and building maintenance cycles. Furthermore, from review of the project's SWMP, the RE identified that the contractor produced 2.20 $x10^3$ m^3 of mixed construction waste. In terms of initial embodied energy, the waste consumption equated to $6.02x10^4$ GJ which corresponds to an additional 11% material phase energy. The RE discovered the contractor initially employed the use of segregated skips (e.g. timber, metal, plastic, cardboard) for all sub-contractors to use, though this method was not maintained during the final stages of the construction phase (i.e. during the labour-intensive internal installation period). Despite the reason not being investigated by the RE, the constant use of the segregated skips would have helped link specific material waste and associated transportation impacts relative to specific construction packages, activities and sub-contractors to increase the granularity of the results. Table 4.41 displays the estimated total waste consumption per material (i.e. waste stream) across each construction package. As there was a 76% difference between the estimated total waste volume (9.30 $x10^3$ m^3) and the reported waste volume (2.20 $x10^3$ m^3), to aid data calculation and comparison, the RE reduced all estimated waste volumes by 76% to discover their relative proportionate value for Project 2. Applying the estimated waste consumption in literature for the specific project type (i.e. 9.30 $x10^3$ m^3), material phase energy would have increased an additional 44% ($2.55x10^5$ GJ). However, the RE acknowledged this simple calculation and the use of the reported mixed waste volumes within the SWMP (i.e. total mixed waste volume that would have included waste streams from outside the reporting scope) would have caused a large degree of uncertainty surrounding the values displayed within Table 4.41.

Table 4.40 Total initial embodied impact per individual life cycle (after Davies et al., 2015, paper 4)

Life Cycle Phase	Embodied Energy (GJ) ±% error (± error value)	Sig (%)[a]	Embodied Carbon (kgCO_2e) ±% error (± error value)	Sig (%)[a]
Material Phase[b]	5.80E+05 ±32% (±1.86E+05)	95.2	6.91E+07 ±32% (±2.21E+07)	97.0
Transportation Phase	1.52E+04 ±32% (±4.86E+03)	2.5	1.03E+06 ±32% (±3.29E+05)	1.5
Construction Phase	1.43E+04 ±32% (±4.57E+03)	2.3	1.10E+06 ±32% (±3.52E+05)	1.5
Total[c]	6.09E+05 ±32% (±1.95E+05)	100	7.12E+07 ±32% (±2.28E+07)	100

[a] Sig: relative significance (%) of each individual life cycle phase in relation to the total value.
[b] Material Phase: total value includes the additional 20% assumed material phase values for the groundworks, electrical and mechanical construction packages.
[c] Life Cycle Phase Totals: totals includes measured values plus additional 3% for non-reporting scope.

Table 4.41 Estimated volume of construction waste consumption and embodied impacts per material for Project 2

Construction Package (Sample)	Material (i.e. Waste Steam)	Volume (m^3)	EE (GJ)[a]	EC (kgCO_2e)[a]
Earthworks	Bricks (e.g. hardcore)	6.83E+01	3.94E+02	3.15E+04
Groundworks	Concrete (e.g. insitu, precast)	3.67E+02	8.53E+02	1.34E+05
Foundations	Inert (e.g. aggregate)	4.49E+02	3.02E+03	2.42E+05
External Walls	Insulation materials (e.g. cladding panels)	6.29E+01	8.10E+01	3.91E+03
Racking	Metals (e.g. steel tubes)	1.34E+02	2.57E+04	2.04E+06
All Packages	Packaging materials (e.g. wrapping)	2.03E+02	2.26E+04	9.28E+05
Syphonic Drainage	Plastic (e.g. HDPE pipe)	4.59E+01	3.74E+03	1.12E+05
All Packages	Timber (e.g. pallets)	2.93E+02	2.05E+03	0.00E+00
M&E	Electrical and electronic equipment (e.g. copper)	1.59E+00	4.46E+02	3.50E+04
Groundworks	Mixed construction & demolition (e.g. concrete)	5.75E+02	1.34E+03	2.10E+05
	Total Waste Consumption per Project	**2.20E+03**	**6.02E+04**	**3.74E+06**
	Waste Benchmark (m^3 per 100 m^2)[b]	2.63E+00		

[a] Totals: EE, embodied energy; EC, embodied carbon.
[b] Benchmark: Industry standard benchmark for project type (normalised per building area and included waste streams).

4.6.2.4 Specified Learning

The fourth research cycle explored the effectiveness of the revised practical framework through the capture and assessment of primary data from a live construction project. The findings emphasised the significance of the explored project's base build (i.e. frame and sub-structure) and external slab which were primarily derived from steel and concrete-based materials, intended to support the function of the building (i.e. transportation and storage of goods). Furthermore, the RE recognised the importance of material selection and the sourcing of project resources to offset certain life cycle impacts. Changes made to the contractor current practices helped detailed data to be captured from both transportation and construction phases, which was linked to the specific construction packages. However, gaps in data were identified and certain assumptions were made by the RE to aid the overall reliability and validity of the findings. Hence, to improve the situation and the provision of future research, the RE identified the following advances: enhanced current practices to capture detailed construction package and project specific data for future benchmarking; increased awareness of the practical challenges which inhibit data capture during a live construction project; and improved consideration towards the practical opportunities which support initial embodied energy reduction during a live construction project.

4.6.3 Research Cycle 5 – Sub-objective 3.2

4.6.3.1 Diagnosing and Action Planning

To achieve sub-objective 3.2, the fifth research cycle continued to explore the effectiveness of the practical framework to assess initial embodied energy consumption within UK non-domestic construction projects. The RE planned to undertake two critical reviews of contractor literature and a quantitative analysis of primary data from a live construction project. In particular, the first review of contractor literature intended to reflect how the contractor is currently addressing initial embodied energy during project tender and pre-construction. Literature highlighted due to the interaction and resources of the contractor during project development, contractors may decide to develop internal bespoke methods to facilitate initial embodied energy assessment rather than use existing tools and databases (Scheuer et al., 2003; Van Ooteghem and Xu, 2012; Davies et al., 2013b; Davies et al., 2014; Srinivasan et al., 2014; Takano et al., 2014). Table 4.29 summarises context and leading questions that formed the basis of the research cycle, which concluded the future paper presented in Appendix H.

Table 4.42 Research cycle 5 content and leading questions

Sub-Objectives[a]	Context	Leading Questions
3.2 Explore Practical Framework	The contractor may decide to develop internal bespoke methods, based upon own current practices and data, to facilitate initial embodied energy assessment rather than use existing LCA tools and databases (Scheuer et al., 2003; Van Ooteghem and Xu, 2012; Davies et al., 2013b; Davies et al., 2014; Srinivasan et al., 2014; Takano et al., 2014).	- How significant is initial embodied energy consideration within project development? - How effective is the revised framework within a different project setting?

[a] Sub-Objectives: MAT, Material life cycle phase; TRAN, Transportation life cycle phase; CON, Construction life cycle phase.

4.6.3.2 Action Taking

In line with the previous research cycle, a mixed methods approach was adopted to facilitate a multi-dimensional view on the subject, which stemmed from the previous review of industry literature (chapter 2) and existing procedure (section 3.2). In particular, due to a different working environment (i.e. different current practices, project teams, construction packages) than previously (see below), the RE made changes to how data would be captured and assessed within the revised practical framework to further establish the effectiveness of the framework towards producing reliable and valid results. Figure 4.19 displays the relationship between the method type, explored data source and findings.

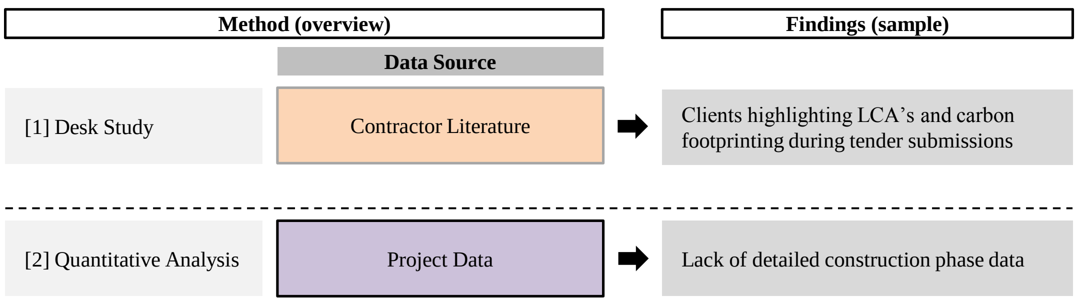


Figure 4.19 Relationship between the method and findings from case study 5

The RE undertook a critical review of contractor literature based upon previous project tender enquiry documents which derived from seven large-scale civil engineering and infrastructure projects. The review aimed to establish the degree of consideration imposed by clients towards addressing initial embodied energy consumption and associated data during previous project tenders. The selection of these particular projects and access to documentation originated from changes to the RE’s role and function within the contactor during the third year of the research project (section 1.2). These changes helped increase the RE’s profile and wider participation within the contractor. Active involvement within two Environmental Steering Groups aided the RE’s understanding of the contactor’s wider operations and environmental management performance within different working environments. Subsequently, scope for further research (i.e. comparison of temporary lighting designs) derived from the RE’s involvement within the Steering Groups, which is presented in Appendix H.

To adapt to new working environment within the explored construction project (see below), the RE undertook another critical review of contractor literature which supported further changes to the revised framework and alternative EPI procedure and sign-in sheets developed within the previous research cycle. In particular, changes were made to the current practices to accommodate the mixed energy supply used during the construction phase (i.e. red diesel and mains electrical) and the unique access control system (i.e. Datascope). Details of the specific changes made to the current practices, including characteristics of the explored construction project, were previously introduced in section 3.3.

The RE undertook a case study in the form of an observational technique and quantitative analysis which further explored the effectiveness of the revised practical framework (derived from the previous review) within a live construction project (i.e. Project 5). Actions undertaken within the case study were primarily aimed to build upon previously attempts to capture detailed data (i.e. research cycle 4), but in particular, further explore the reliability and validity of the revised framework within a different project type and operating division within the contractor, which would include inherent differences (e.g. current practices, project teams, construction packages).

Due to the scale of the construction project and timeframe of the overall research project, the RE decided to build upon the findings from previous research cycles and industry literature (Scheuer et al., 2003; Goggins et al., 2010; Jiao et al., 2012; Cabeza et al., 2013; Wu et al., 2014) by exploring the project's base-build (i.e. frame and sub-structure). The base-build comprised of the following construction packages which primarily contained steel and concrete-based materials: foundations, earthworks and groundworks, reinforced concrete frame, and steel frame. The RE was actively involved throughout the entire construction phase of the project (i.e. 90 weeks), though in line with the base-build programme and recommendations from the industrial supervisors, only first 55 weeks of the project was explored. The RE employed the same non-intrusive participant observation technique, as presented within research cycle 4, to gather a detailed account of primary data. Captured project data within the contractor current practices was analysed through multiple Microsoft Excel spreadsheets in line with the methodology previously described in section 3.4. Subsequently, scope for further research (i.e. integrated approach towards initial embodied energy reduction) stemmed from the RE's involvement within the project, which is presented in Appendix H.

4.6.3.3 Evaluating

From the first review of contractor literature, the RE acknowledged similarities throughout the questions presented by clients and corresponding contractor answers. Table 4.43 provides an example (e.g. Project 1) of the key findings derived from the review of the project tender enquiry documents from the large-scale civil engineering and infrastructure projects. Commonly clients proposed questions to the contractor with regards to examples of previous environmental management best practice, the use of low embodied carbon (or energy) materials (Harris, 1999; Chen et al., 2001), methods of capturing and reducing life cycle impacts (embodied and operational), previous project environmental assessment performances (i.e. BREEAM, CEEQUAL) (Energy Saving Trust, 2009; Doran and Anderson, 2011), and the need for organisation environmental accreditation (e.g. ISO 14001) (Biondi et al., 2000; Nakamura et al., 2001). The contractor emphasised a commitment towards using Building Information Modelling (BIM) to initiate an integrated approach towards design and construction and willingness to model carbon (or energy) data across different project life cycle phases (Vilkner et al., 2007; Goedert and Meadati, 2008; Mah et al., 2010; Wu et al., 2014). However, only Project 6 (Appendix I) documentation provided evidence of data sources which would be used to undertake this task (IEMA, 2010; Goggins et al., 2010; Rai et al., 2011). Seemingly the importance of project environmental performance varied throughout. With regards to Project 1 (Appendix I), questions relating to the environmental agenda of the project were weighted as 2% of the total scope of the tender whereas for Project 4 (Appendix I) the environmental agenda (including quality) was weighted as 30% of the total. Nonetheless, the majority of project tender scopes emphasised the importance of project cost, planning and the overall capability of the contractor (Anderson and Mills, 2002; Sodagar and Fieldson, 2008). A detailed review of all remaining tender enquiry documents per large-scale civil engineering and infrastructure project is presented within Appendix I.

Table 4.43 Key findings from the review of project 1 tender enquiry documents

Project Details	Key Findings
Project Name Project 1 **Client Type** Client A **Project Value** £140 million **Project Start Date** Start April 2014 **Project Description** New build large-scale rail depot located South England **Documents Reviewed** Document No. 1 Document No. 7	- The client expected 20% of their operational energy use to derive from renewable sources and aimed to benefit from substantial improvements to life cycle running costs; - The contractor planned to integrate a selection of renewables (e.g. photovoltaic panels, solar thermal panels, combined heat and power, ground source heat pump) to achieve client expectations. Emphasis towards renewables is in agreement with Buchanan and Honey (1994), Pries (2003), Kohler et al. (2006), DECC (2009b) and Liu et al. (2014); - No emphasis towards initial embodied impacts or demolition embodied impacts were identified by the client. Lack of emphasis towards initial embodied energy is in accordance with BIS (2010), RICS (2010) and Monahan and Powell (2011); - The client noted a minimum of a Very Good BREEAM 2011 rating for their project as a practical completion requirement. Emphasis towards BREEAM is in agreement with Energy Saving Trust (2009), Doran and Anderson (2011) and BREEAM (2014b); - The client proposed no minimum rating per individual BREEAM section (e.g. management, energy, materials); - The contractor highlighted a commitment to only procure high Green Guide rating materials (i.e. A or A+) and only use suppliers that have an ISO 14001 accreditation. Emphasis towards Green Guide is in agreement with Fieldson and Rai (2009), Halcrow Yolles (2010) and Anderson et al. (2011) whereby commitment towards ISO 14001 accreditation is in agreement with Biondi et al. (2000) and Nakamura et al. (2001); - The contractor highlighted that thermal insulation products used would have a low embodied impact relative to their thermal properties; - The contractor targeted reduced material phase impact with regards to external walls, windows, roof, upper floor slab, internal walls, and floor finishes construction packages in line with BREEAM requirements; - The contractor identified that all sub-contractors are required to use low energy plant and equipment. Emphasis towards low energy plant is in agreement with RICS (2008) and Ko (2010); - The profile of the contractor's environmental manager had no reference to LCA awareness; - The client outlined that the environmental agenda of the project had a 2% weighting on the overall project tender submission in contrast to project planning and project management which were weighted as 28% and 18% respectively. Emphasis towards construction programme is in agreement with Anderson and Mills (2002) and Sodagar and Fieldson (2008); - No direct reference was made towards the use and benefit of an LCA by the client or contractor.

From the second review of contractor literature, the RE acknowledged that the contractor used a unique external on-line electronic access control system (i.e. Datascope) to record basic operative occupational information (e.g. sub-contractor, home location, travel distance, transportation type) and coordinate deliveries of project resources. Providing occupational information during the site inductions allowed operatives to gain access to site through the main site entrance within the on-site accommodation. The access control system captured operative movements on a daily basis and allowed the RE to obtain daily print-outs of the data. Plant and equipment and material movements were booked in by sub-contractor operatives by completing an on-line form. The on-line form was designed to only allow a specific number of deliveries per delivery slot (i.e. two deliveries per 15 minute interval) and prevent unauthorised deliveries to help the contractor improve coordination of on-site logistics and reduce transportation congestion surrounding the project. Overall, the use of the electronic version of the sign-in sheets intended to improve data reliability and validity by making it easier for individuals to input consistent and complete data in line with the data requirements of the revised framework. Furthermore, in terms of construction phase energy, the RE discovered that the contractor used both red diesel and electrical energy (from the national grid) to power on-site operations such as: the on-site accommodation for the contractor and sub-contractor operatives; the use of small-scale plant and equipment on-site by sub-contractor operatives; the erection and movement of two slip-form frames (i.e. both concrete frame cores); and the function of two large tower cranes which were used by all sub-contractors to facilitate the use of project resources. Hence, to determine the electrical energy consumption of each construction package, the RE decided to pro-rata the on-site electrical energy meter readings against operative man days per sub-contractor. These electrical energy values were added to the fuel consumption values captured within the alternative EPI procedure.

To determine the overall effectiveness of the revised framework within Project 3, the reporting scope (i.e. system boundaries) of the case study was first established. The RE discovered that the explored construction packages represented 11% of the total population of construction packages available within the study. As highlighted previously, interpretation of all construction packages was beyond the scope of the study, though the RE recognised the following construction packages which formed the non-reporting scope (selected few): external and internal walls (glazed façade), lifts and escalators, mechanical and electrical, sprinklers, staircases, ceramic tiling, raised access flooring, ceilings and partitions, decorating and furniture, and professional services. The RE recognised that including these construction packages within the study would increase the reported embodied energy consumption values (see below) especially as certain construction packages (e.g. lifts and escalators) were based upon the use of energy intensive materials (e.g. steel). Notably, considering transportation phase energy, the RE discovered that the internal and external glazed façade panels and ceramic tiles were manufactured and transported from central Europe, which if measured, would have significantly impacted results.

From the use of the revised practical framework within Project 3, in terms of the material phase, the RE discovered the steel frame as the most significant construction package accounting for 65% of total material phase energy despite only contributing to 4% and 11% of total material volume and mass respectively. Table 4.44 illustrates the data type, data source and calculation methods used to assess the material phase impacts relative to individual construction packages.

Table 4.44 Material phase impacts (energy and carbon) and calculation methods per construction package for Project 3

		Ref.	A[a]	B[c]	C	D[a]	E[a]	F	G	H[c]	I	J
Construction Package	**Main Component Name**	**Note**	Density (kg/m^3)	Total Volume of Material (m^3)	Total Mass (kg) Whole Building [A x B]	EE per mass (MJ/kg)	EC per mass (kgCO$_2$e /kg)	EE (MJ) for Whole Building [C x D]	EC (kgCO$_2$e) for Whole Building [C x E]	Total Building Area (m^2)	EE per m^2 (MJ/m^2) Whole Building [F / H]	EC per m^2 (kgCO$_2$e/ m^2) Whole Building [G / H]
Foundations	Insitu Concrete	Inc. rebar	2.40E+03	4.12E+03	9.88E+06	2.61	0.26	2.58E+07	2.57E+06	5.07E+04	5.09E+02	5.07E+01
Earthworks / Groundworks	Insitu Concrete	Foundations (inc. rebar)	2.40E+03	3.37E+03	8.08E+06	2.03	0.22	1.64E+07	1.78E+06	5.07E+04	3.23E+02	3.51E+01
	Drainage	Cast Iron	7.87E+03	1.10E+00	8.66E+03	25.0	1.91	2.16E+05	1.65E+04	5.07E+04	4.27E+00	3.30E-01
	Drainage	HDPE[b]	9.65E+02	6.00E-01	5.79E+02	76.7	1.60	4.44E+04	9.26E+02	5.07E+04	8.80E-01	2.00E-02
RC Frame	Insitu Concrete	Basement to Level 1 (inc. rebar)	2.40E+03	4.77E+03	1.14E+07	2.03	0.22	2.32E+07	2.52E+06	5.07E+04	4.58E+02	4.96E+01
	Insitu Concrete	Level 2 to Roof (inc. rebar)	2.40E+03	6.70E+03	1.61E+07	2.03	0.22	3.27E+07	3.54E+06	5.07E+04	6.44E+02	6.98E+01
Steel Frame	Steel Frame	Columns and Beams	7.80E+03	5.18E+02	4.04E+06	35.3	2.57	1.43E+08	1.04E+07	5.07E+04	2.81E+03	2.05E+02
	Steel Deck		7.80E+03	1.76E+02	1.37E+06	31.5	2.51	4.31E+07	3.44E+06	5.07E+04	8.51E+02	6.78E+01

[a] Data obtained from the ICE material database (external literature)
[b] Data obtained from the British Plastics Federation (external literature) (BPF, 2014)
[c] Data obtained from the bill of quantities and design drawings (contractor current practices)

The RE discovered that material movements represented 28% of the total transportation phase impacts whereby the steel frame package was the most significant construction package; representing 41% of the total. Plant and equipment movements accounted for the largest proportion of transportation phase impacts (41%). The earthworks and groundworks sub-contractor was the most significant construction package (34%) with the transfer of waste soil derived from their on-site operations to the waste transfer station (68 km from the site) resembled 54% of total. Operative transportation represented 31% of the total transportation phase impacts whereby the steel frame, RC frame and main contractor were responsible for 35%, 33% and 19% of the total respectively. Figure 4.20 displays the overall transportation phase impact per construction package.

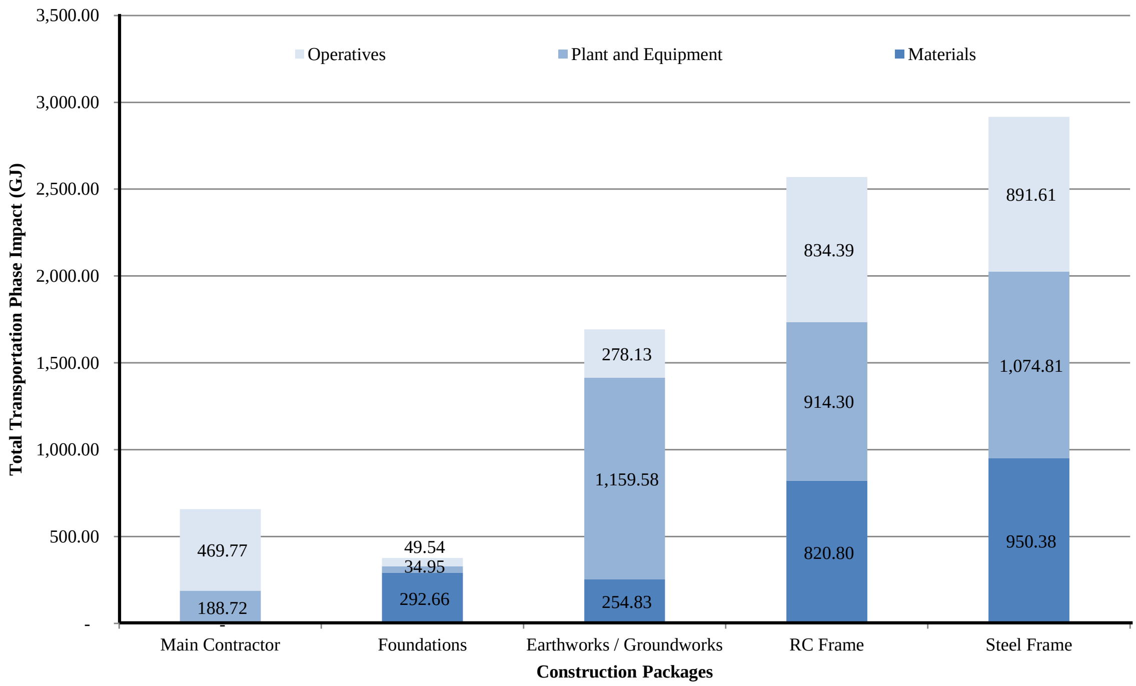


Figure 4.20 Transportation phase impact per construction package for case study 5

In terms of the construction phase, the RE discovered the RC frame as the most significant construction package accounting for 44% of total construction phase energy. Figure 4.21 displays the relationship between operative numbers and energy use on-site (red diesel and electrical energy) per construction package in relation to the construction programme. From the findings, there was no constant positive relationship between operative numbers and on-site energy consumption. During months 3 to 4, the number of operatives increased whereas energy consumption fell. On average, an individual operative was responsible for 1.36×10^{-1}

GJ (0.136 GJ) of the total energy consumption per day throughout the construction phase. Evidently, during December 2013 operative numbers and energy consumption reduced as expected by the RE due to the annual holiday period as on-site operations were temporarily stopped. Figure 4.22 illustrates a comparison between the relative significance of red diesel and electrical energy use during the construction phase. Evidently, in line with previous industry literature (Ko, 2010; Monahan and Powell, 2011), the reliance upon red diesel to support on-site operations progressively declined during project progression, mainly due to the early completion of many red diesel fuelled plant-intensive construction packages. The RE recognised during the completion of the ground and earthworks package (end of the 6th month), this was the first stage of the project when electrical energy use was more predominant (depicted by the crossover of the linear trend lines within the table); a trend which continued throughout. Overall, red diesel and electrical energy provided 51% and 49% of the total construction phase energy respectively.

Operative (No. Man Days)	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14	Feb-14
Main Contractor	8	471	407	496	434	429	536	466	496	571	268	598	477
Foundations	2	143											
Earthworks and Groundworks	3	679	1,232	2,169	1,921	1,647							
RC Frame			411	723	640	549	984	298	651	863	519	941	724
Steel Frame						60	333	497	579	745	256	271	181
Total per Month	13	1,293	2,049	3,388	2,995	2,685	1,853	1,261	1,726	2,179	1,043	1,810	1,382
Running Total	13	1,306	3,355	6,743	9,738	12,423	14,276	15,537	17,263	19,442	20,485	22,295	23,677

Electrical Energy Use (GJ)	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14	Feb-14
Main Contractor	19	35	13	14	13	11	25	38	34	53	43	90	78
Foundations	5	11											
Earthworks and Groundworks	7	51	30	47	42	31							
RC Frame			10	16	14	10	45	25	44	81	84	142	119
Steel Frame	-	-	-	-	-	1	15	41	39	70	42	41	30
Total per Month	30	97	54	77	69	53	85	104	118	204	169	272	226
Running Total	30	127	181	258	327	380	465	569	686	890	1,059	1,331	1,558

Red Diesel Use (GJ)	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14	Feb-14
Main Contractor	-	-	-	-	-	-	-	-	-	-	-	37	37
Foundations	215	117											
Earthworks and Groundworks	144	382	189	70	11	29							
RC Frame			63	23	4	10	39	39	39	39	4	4	-
Steel Frame	-	-	-	-	-	-	39	39	39	39	4	16	-
Total per Month	359	499	252	94	15	39	78	78	78	78	8	57	37
Running Total	359	858	1,110	1,204	1,218	1,258	1,336	1,414	1,492	1,570	1,578	1,635	1,672

Total Energy Use (GJ)	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14	Feb-14
Main Contractor	19	35	13	14	13	11	25	38	34	53	43	127	115
Foundations	220	128											
Earthworks and Groundworks	151	433	219	117	54	60							
RC Frame			73	39	18	20	84	64	83	120	88	146	119
Steel Frame						1	54	80	78	109	45	56	30
Total per Month	390	596	305	171	84	92	163	182	196	282	177	329	264
Running Total	390	985	1,291	1,461	1,546	1,638	1,801	1,983	2,178	2,460	2,637	2,966	3,230

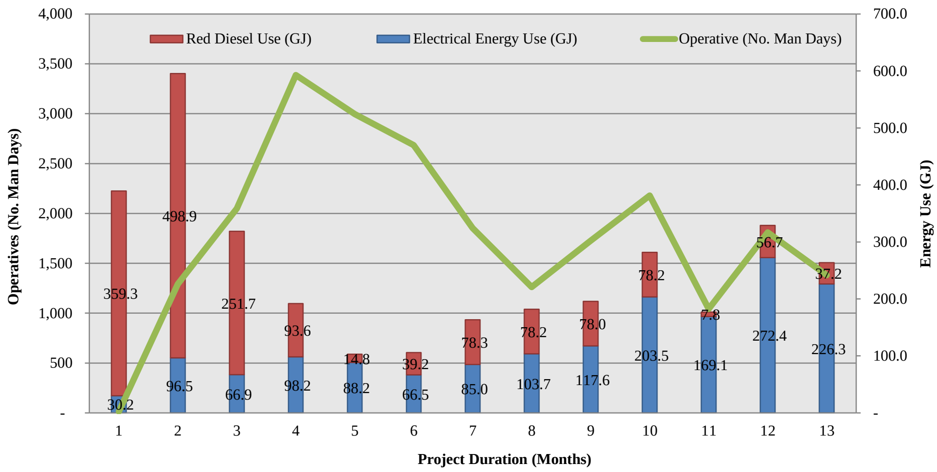


Figure 4.21 Summary of construction phase data for Project 3

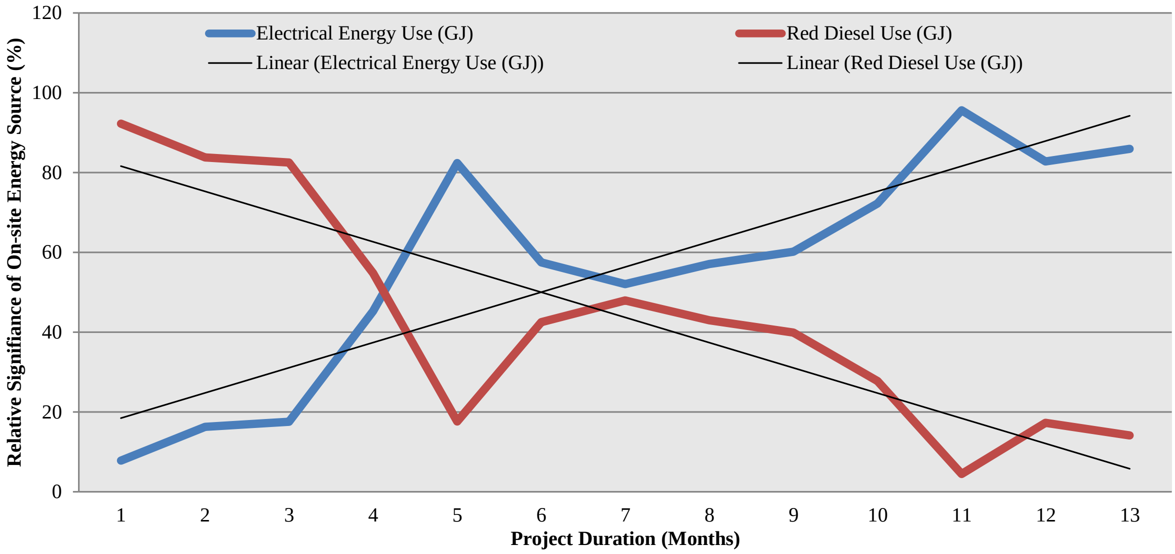


Figure 4.22 Comparison between the relative significance of on-site energy sources (red diesel and electrical energy) for Project 3

Due to project lead-in and the relationship between certain construction packages (e.g. following on trades), during the final 13 weeks of data capture (week 43 to 55) the RE acknowledged that some of the construction packages outside the reporting scope commenced on-site. Notably this impacted data capture and assessment in particular with regards to construction phase energy. As operatives related to these construction packages consumed electrical energy on-site (i.e. via hand tools), the RE was unable to calculate and differentiate these specific impacts from the weekly energy meter readings; as these work areas within the project were not sub-metered or separate from the main temporary electrical power supply. Consequently, the RE recognised that in this instance the measured value would be an overestimate of the true value (i.e. actual construction phase energy use) due to the measurement error (i.e. energy use from the non-reporting scope). Table 4.45 summarises the total measured values discovered by the RE and the associated uncertainty (i.e. measurement error) in relation to the lower and upper bound limits for each individual life cycle phase.

Table 4.45 Total initial embodied energy consumption per construction package (Project 3)

Construction Package	Material Phase	Transportation Phase			Construction Phase	Total	Overal l Rank
		Materials	Plant and Equipment	Operatives			
Steel Frame	1.86E+05	9.50E+02	1.07E+03	8.92E+02	4.55E+02	1.89E+05	1st
RC Frame	5.59E+04	8.21E+02	9.14E+02	8.34E+02	1.46E+03	5.99E+04	2nd
Foundations	2.58E+04	2.93E+02	3.50E+01	4.95E+01	3.48E+02	2.65E+04	3rd
E & Groundworks	1.67E+04	2.55E+02	1.16E+03	2.78E+02	4.88E+02	1.88E+04	4th
Main Contractor	0.00E+00	0.00E+00	1.89E+02	4.70E+02	5.41E+02	1.20E+03	5th
Totals (Measured)[a]	2.84E+05	2.32E+03	3.37E+03	2.52E+03	3.29E+03	2.95E+05	
Tot' (Lower Limit)[a]	1.93E+05	1.58E+03	2.29E+03	1.72E+03	2.24E+03	2.01E+05	
Tot' (Upper Limit)[a]	3.75E+05	3.06E+03	4.45E+03	3.33E+03	4.35E+03	3.90E+05	

[a] Totals: Measured, measured value discovered from Project 1 data (i.e. table data); Lower Limit, lowest possible value (i.e. -32%); Upper Limit, highest possible value (i.e. +32%).

Table 4.46 displays the range of total initial embodied energy consumption values per individual life cycle phase due to errors within the measured values (i.e. quantities and rates). The RE discovered a maximum total initial embodied energy consumption value of 3.91×10^5 GJ (391,000 GJ) and the minimum value of 2.01×10^5 (201,000 GJ) for Project 3. Figure 4.23 illustrates the change in the relative significance of each individual life cycle phase due to errors within the measured values, whereby the significance of construciton phase energy varied between 2.1% and 1.1% of the total respectively.

Table 4.46 Range of total initial embodied energy consumption values (GJ) per individual life cycle phase due to uncertainty (Project 3)

Upper and Lower Bound Limit Combinations (MAT-TRAN-CON)	Material Phase (GJ)	Transportation Phase (GJ)	Construction Phase (GJ)	Total Initial Embodied Energy (GJ)
[1] Up-Up-Up	3.75E+05	1.08E+04	4.35E+03	3.91E+05 (i.e. Max)
[2] Up-Up-Low	3.75E+05	1.08E+04	2.24E+03	3.88E+05
[3] Up-Low-Up	3.75E+05	5.58E+03	4.35E+03	3.85E+05
[4] Up-Low-Low	3.75E+05	5.58E+03	2.24E+03	3.83E+05
[5] Low-Up-Up	1.93E+05	1.08E+04	4.35E+03	2.09E+05
[6] Low-Up-Low	1.93E+05	1.08E+04	2.24E+03	2.06E+05
[7] Low-Low-Up	1.93E+05	5.58E+03	4.35E+03	2.03E+05
[8] Low-Low-Low	1.93E+05	5.58E+03	2.24E+03	2.01E+05 (i.e. Min)
Range[b]	1.82E+05	5.25E+03	2.11E+03	1.89E+05
Measured Value [c]	2.84E+05	8.21E+03	3.29E+03	2.96E+05
Error Value (±32%)[d]	9.10E+04	2.63E+03	1.05E+03	9.47E+04

[a] Combinations: potential maximum and minimum value per individual life cycle phase (material-transportation-construction); Up, upper bound limit (i.e. -32%); Low, lower bound limit (i.e. +32%).
[b] Range: Up-Up-Up values minus Low-Low-Low values (i.e. the maximum minus the minimum value).
[c] Measured Value: measured value from data captured within Project 3 (i.e. 0% error)
[d] Error Value: difference between the measured value and upper or lower bound limits (i.e. ±32% error derived from the quantities and rates).

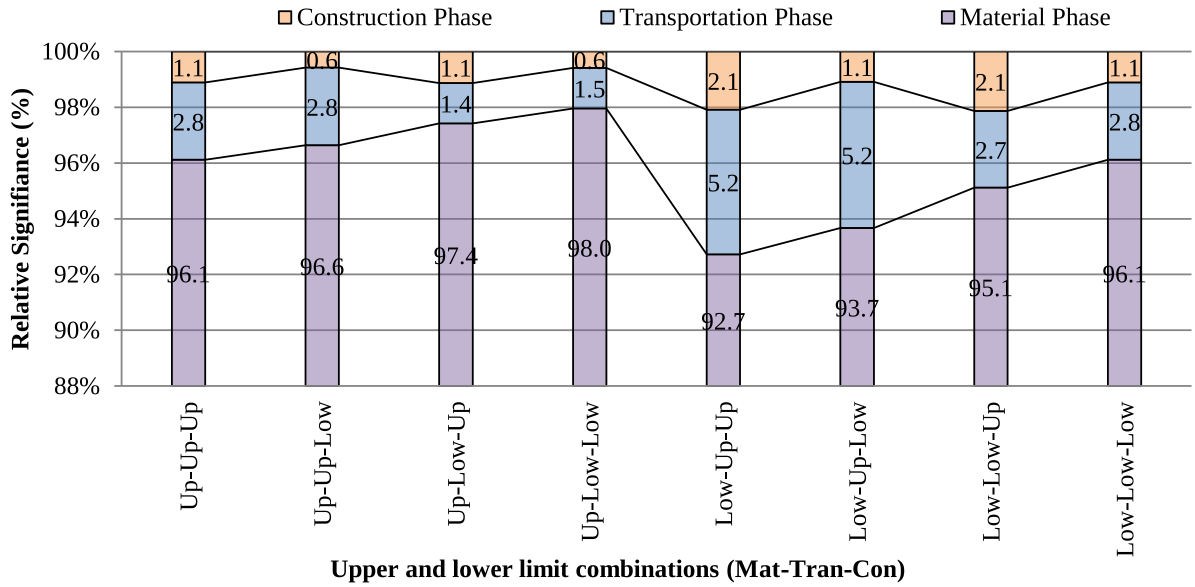


Figure 4.23 Comparison between the possible relative significance values (%) per individual life cycle phase due to uncertainty (Project 3)

Similar to the previous research cycle, the RE established certain assumptions to overcome gaps in data identified during the capture and processing of data. Table 4.47 displays a comparison between the reporting scope and non-reporting scope within Project 3. As data was only captured during the first 55 weeks of the construction project, to improve data reliability and validity, the RE estimated the significance of the reporting and non-reporting scope in addition to how much data was captured in total in comparison to the total population of data available. Through a comparison between the contents of the construction packages (i.e. materials used, package duration) and professional judgement, the RE calculated that the reporting scope was responsible for 70% of the total embodied energy impact and population of data available, with the non-reporting scope responsible for the remaining 30%.

Table 4.47 Comparison between the reporting scope (i.e. measured values) and non-reporting scope (i.e. data gaps) for Project 3

Life Cycle Phase Data[a]	Reporting Scope (i.e. sample data) (% of total data available)	Non-reporting Scope (i.e. non-sample) (% of total data available)
No. of Construction Packages	**5 (11%)**	**40 (89%)**
Material Phase Data	35%	65%
Transportation Phase – Material Data	40%	60%
Transportation Phase – Plant Data	40%	60%
Transportation Phase – Operatives Data	40%	60%
Construction Phase Data	65%	35%
% of Total Population of Data	70% of total	30% of total

[a] Life Cycle Phase Data: Construction Packages, obtained from a review of the PoW; Material Phase Data, assumed to be liked to Project Turnover (same approach as previous research cycle); Transportation Phase, obtained from sign-in sheet data; Construction Phase, obtained from sign-in sheet and EPI Procedure data.
[b] % Total: values within the reporting scope estimated to represent 97% of total whereas values within non-reporting scope estimated to represent 3% of total.

Table 4.48 displays the total initial embodied impact (energy and carbon) per individual life cycle phase, including consideration towards all previous assumptions and gaps in data. Evidently, the material phase impact was responsible for 96% of the total initial embodied energy and carbon. As expected, the steel frame construction package was the most significant overall and accounted for 65%, 35% and 14% of total material, transportation and construction phase energy respectively.

Table 4.48 Total initial embodied impact per individual life cycle for Project 3

Life Cycle Phase	Embodied Energy (GJ) ±% error (± error value)	Sig (%)[a]	Embodied Carbon (kgCO_2e) ±% error (± error value)	Sig (%)[a]
Material Phase[b]	3.70E+05 ±32% (±1.18E+05)	96.1	3.15E+07 ±32% (±1.01E+07)	96.4
Transportation Phase	1.07E+04 ±32% (±3.42+03)	2.8	7.28E+05 ±32% (±2.32E+05)	2.2
Construction Phase	4.28E+03 ±32% (±1.37E+03)	1.1	4.57E+05 ±32% (±1.46E+05)	1.4
Total[b]	3.85E+05 ±32% (±1.23E+05)	100	3.27E+07 ±32% (±1.05E+07)	100

[a] Sig: relative significance (%) of each individual life cycle phase in relation to the total value.
[b] Life Cycle Phase Totals: totals includes measured values plus additional 30% for non-reporting scope.

Furthermore, from review of the project's SWMP, the RE identified that the contractor produced 5.04 $x10^3$ m^3 of mixed construction waste, which was 13% less than the total estimated volume of waste defined in literature (i.e. 5.83 $x10^3$ m^3). Hence, in terms of initial embodied energy, the reported waste consumption equated to $1.56x10^5$ GJ which corresponded to an additional 42% material phase energy. Overall, from the use of the revised practical framework within a different working environment, the RE identified additional issues than previously raised which inhibited the capture and assessment of data through the existing or alternative current practices. Table 4.50 summaries the key practical challenges which impacted the overall results. The RE recognised overcoming these practical challenges would result in improved data validity and reduce data gaps whilst using the revised framework to explore additional construction projects within future research.

Table 4.49 Estimated volume of construction waste consumption and embodied impacts per material for Project 3

Construction Package (Sample)	Material (i.e. Waste Steam)	Volume (m^3)	EE (GJ)[a]	EC ($kgCO_2e$)[a]
Earthworks	Bricks (e.g. hardcore)	2.27E+02	1.31E+03	1.05E+05
RC Frame	Concrete (e.g. insitu, precast)	4.87E+02	1.13E+03	1.78E+05
Foundations	Inert (e.g. aggregate)	7.70E+02	5.18E+03	4.14E+05
Steel Frame	Metals (e.g. steel tubes)	2.18E+02	4.17E+04	3.31E+06
All Packages	Packaging materials (e.g. wrapping)	8.73E+02	9.70E+04	3.99E+06
All Packages	Timber (e.g. pallets)	9.08E+02	6.36E+03	0.00E+00
Groundworks	Mixed construction & demolition (e.g. concrete)	1.56E+03	3.62E+03	5.68E+05
	Total Waste Consumption per Project	**5.04E+03**	**1.56E+05**	**8.57E+06**
	Waste Benchmark (m^3 per 100 m^2)[b]	**9.94E+00**		

[a] Totals: EE, embodied energy; EC, embodied carbon.
[b] Benchmark: Industry standard benchmark for project type (normalised per building area and included waste streams).

Table 4.50 Key issues derived during data capture and assessment within Project 3

Life Cycle Phase	Key Issues
Material Phase	- Difficult to gain access to full content of BoQ due to commercial sensitivity; - Difficult to assess material quantities due to vast number of complex design drawings.
Transportation Phase	- Project site had two delivery entrances which increased the number of deliveries; - The improved sign-in sheets (i.e. hard copies) were used during instances when alterations were made to the site delivery entrances (i.e. closures, relocations), when electrical power was temporary lost (i.e. power outage), and when unplanned deliveries or delivery errors occurred (i.e. too many deliveries per slot); - Information captured on the on-line forms (i.e. booking deliveries) contained vast incomplete, incoherent information which was difficult to use without requesting clarification from contractor operatives.
Construction Phase	- Difficult to accurately identify electrical energy consumption per construction package (i.e. value was normalised for each operative man day per sub-contractor per month); - Electrical energy consumption varied significantly throughout the project with no clear cause of this occurrence; - Difficult to correlate which items of plant and equipment were responsible for red diesel use; - Difficult to link operatives to specific construction packages and activities per sub-contractor due to static information captured during operative site induction (i.e. does not allow for change in circumstances); - Difficult to quantify electrical energy use caused by the two tower cranes in relation to construction activities as these were not metered individually; - Difficult to quantify electrical energy use caused by the two slip-form frames in relation to the RC frame construction package as these were not metered individually; - Instances whereby electrical power was temporary lost (i.e. power outage) were not captured in detail.
All Initial	- Only five construction packages (including the contractor) were explored hence the overall initial

Embodied Energy Phases	embodied energy performance of the project would be significantly greater than reported; - Difficult to acknowledge and correlate the specific construction activities to the correct construction packages and sub-contractors; - Difficult to accurately acknowledge the significance of the earthworks and groundworks and the RC frame construction packages as these were procured by the same sub-contractor (i.e. shared project resources); - Despite only 5 construction packages were explored, additional construction packages were operational during the last few months of data capture, thus difficult to accurately address the construction phase impact to each sub-contractor; - Despite the on-site accommodation not physically being located on the building site, this accommodation was not separately metered (i.e. electrical meter) thus its significance is unclear.

4.6.3.4 Specified Learning

The fifth research cycle explored the effectiveness of the revised practical framework through the capture and assessment of primary data from a live construction project. The findings emphasised the significance of the steel frame construction package in comparison to all other base-build construction packages. Despite the production of detailed results, many difficulties emerged when capturing and assessing data in particular with regards to accurately accounting for construction phase energy per sub-contractor from electrical energy meter readings as values were not sub-metered and therefore had to pro rata against operative numbers. Furthermore, the RE recognised the emphasis clients have place previously on understanding environmental management best practice and methods of reducing life cycle impacts during project tender submissions, where the contractor commonly highlighted their commitment towards using BIM to model carbon (or energy) data across different project life cycle phases. Hence, to improve the situation and the provision of future research, the RE identified the following advances: enhanced approach towards accurately accounting for construction phase energy per sub-contractor during the use of mixed energy sources; improved awareness of project stakeholders involved and decisions made during pre-construction to address initial embodied energy consumption; increased comprehension of how initial embodied energy datasets can be integrated into BIM models to explore the modelling and predicting of data.

4.6.4 Updated Research Progression

Figure 4.24 illustrates the progression of the research after completion of the third overarching objective and associated sub-objectives and case studies.

Figure 4.24 Research progress at completion of the third overarching objective

4.7 Overarching Objective Four

The purpose of the fourth overarching objective was to examine the practical challenges and opportunities for the contractor to address initial embodied energy consumption within UK non-domestic construction projects. In order to establish the practical challenges and opportunities, the RE first undertook a comparison of all captured construction project data derived from the previous three research cycles. The comparison aimed to reflect differences between the explored construction projects and the associated key findings from the use of the practical framework.

4.7.1 Construction Project Data Evaluation

Table 4.51 summarises the basic characteristics of the three explored construction projects detailed previously within research cycles 3, 4 and 5. Project 1 and 2 were the same project type (industrial warehouse) whereby data was captured by the RE for the entirety of the project durations, though only data from the first 55 weeks was captured for Project 3. Despite not being fully investigated, the RE acknowledged the importance of project location in terms of potentially reducing initial embodied energy consumption, as it is widely recognised within the UK construction industry that a significant proportion of project resources (i.e. materials, plant and equipment, and operatives) and overall construction work are located within the south of England which can influence relative transportation impacts due to the vast surrounding road, rail and air infrastructure (CITB, 2015; Schouten, 2015).

Table 4.51 Comparison between the basic characteristics of each construction project

Project Characteristics	Project 1	Project 2	Project 3
Project Type	Industrial Warehouse	Industrial Warehouse	Multi-storey commercial office
Project Description	Three storey office, two small external offices and three internalised temperature controlled chambers. Prefabricated steel structure, composite roof and cladding panels.	Two small external offices, a single storey mezzanine office and a large chamber. Prefabricated steel structure, composite roof and cladding panels.	Car park, police station, bicycle interchange and multiple retail spaces. Two reinforced concrete cores, mixed concrete (lower floors) and prefabricated steel structure (upper floors) and unitised cladding panels.
Project Location	South of England	South of England	South of England
Project Building Area	19,564 m^2	86,000 m^2	50,700 m^2
Project Duration (Start)	30 weeks (Oct 2011)	30 weeks (Jan 2012)	90 weeks (Mar 2013)
Case Study Duration	30 weeks	30 weeks	55 weeks

Table 4.52 displays the amount of project data captured and assessed by the RE through each explored construction project. The difference in values between the total project data and reporting scope (i.e. system boundary) provides evidence of the overall uncertainty within the results in terms of reflecting the true initial embodied energy values for each construction project. Nonetheless, from the RE’s professional judgement it was estimated that 97% of the total initial embodied energy consumption was derived from the explored construction packages within Project 2. The RE recognised despite many construction packages were not evaluated (e.g. staircases, soft landscaping, ceramic tiling, joinery) the corresponding impact from these packages would be small, and therefore only an additional 3% was added to the total initial embodied energy consumption reported by the RE to represent these non-reporting scope packages. The RE used the same approach to address Project 1 (due to similarities in project type, building features and non-explored construction packages) though as only a

small proportion of transportation phase impacts were captured (see below) the non-reporting scope was deemed to represent an additional 10% to the total initial embodied energy consumption. The RE estimated the non-reporting scope for Project 3 related to 30% of the total initial embodied energy consumption which related to construction packages such as: external and internal walls (glazed façade), lifts and escalators, mechanical and electrical, and sprinklers. Overall, reducing these data gaps and assumptions through a complete assessment of all available project data (i.e. all materials, plant and equipment, and operatives across all construction packages) would have further improved the overall reliability and validity of the results. However, the additional time and resources required may not be justifiable in terms of the overall output and usefulness of increased detailed data.

Table 4.52 Comparison between the total reporting and non-reporting scopes in relation to explored construction packages (system boundaries) per construction project

Reporting Scope (i.e. System Boundaries)[a]	Project 1	Project 2	Project 3
Total Project Data (Sig.)[a]	36 No. (100%)	40 No. (100%)	45 No. (100%)
Reporting Scope (Sig.)	16 No. (44%)	15 No. (38%)	5 No. (11%)
Non-reporting Scope (Sig.)	20 No. (66%)	25 No. (62%)	40 No. (89%)
Total EE Impact	**90% of Total EE**	**97% of Total EE**	**70% of Total EE**

[a] Totals: relate to the number of construction packages explored within the construction project.

Table 4.53 demonstrates the project data captured relative to the total population of data available per individual life cycle phase. Evidently limited transportation phase impacts were captured during Project 1 due to weaknesses noted within the contractor's existing sign-in sheets (section 4.6.1). Project 2 benefited from changes made to the sign-in sheets (i.e. the new sign-in sheets Forms 'A', 'B' and 'C') as 92% of all material and 64% of all operative transportation impacts were captured as a consequence. As Project 3 only focused on specific construction packages (i.e. base-build packages) the RE estimated that only 40% of total transportation phase data was captured and reflected within the project's total transportation phase energy consumption.

Table 4.53 Comparison between the reporting scopes in relation to individual life cycle phases per construction project

Reporting Scope Details[a]	Project 1	Project 2	Project 3
Total Project Data (Sig.)	16 No. (44%)	15 No. (38%)	5 No. (11%)
MAT Data	81%	81%	35%
TRAN – Material	0%	92%	40%
TRAN – P&E	5%	92%	40%
TRAN – Operatives	0%	64%	40%
CON Data	44%	38%	11%
Total EE Impact	**90% of Total EE**	**97% of Total EE**	**70% of Total EE**

[a] Totals: relate to the amount of data captured per life cycle phase (MAT, material phase; TRAN, transportation phase; CON, construction phase; P&E, plant and equipment).

Table 4.54 presents the number and type of current practices used by the RE to support the data requirements of the practical framework. The RE used eight existing (original) current practices typically used by the contractor within Project 1 to determine their overall use and to support an initial embodied energy assessment. The findings derived from Project 1 (section 4.6.2) supported the development of alternative current practices within Project 2, whereby the EPI procedure and sign-in sheets were further modified within Project 3 due to changes in working environment. Evidently the use of the BoQ and design drawings was maintained throughout, as these current practices provided the RE with the require material phase data (i.e. material characteristics). The resource database was not used within Project 2 or 3 as the current practice was being phased out (i.e. removed) by the contractor during the timescale of the research project. The SWMP was used throughout to provide waste consumption data (where applicable) and transportation phase data (i.e. number and location of waste transfers). The RE recognised the completeness and detail of data within the current practices (either original or alternative) had a direct impact on the overall reliability and validity of the results; especially as it was previously noted (section 2.4) data source selection is a key parameter of any LCA study.

Table 4.54 Comparison between the explored and developed current practices per construction project

Current Practices (i.e. Data Sources)	Project 1	Project 2	Project 3
BoQ	Original	Original	Original
Design Drawings	Original	Original	Original
Resource Database	Original	-	-
Plant Register	Original	Alternative	Alternative
EPI Procedure	Original	Alternative	Modified Alternative
Sign-in Sheets	Original	Alternative	Modified Alternative
PoW	Original	Alternative	Alternative
SWMP	Original	Original	Original

Table 4.55 illustrates the total initial embodied energy consumption per construction package across each explored construction project. As Project 1 and 2 were the same project type (i.e. industrial warehouse) similar construction packages were explored, whereby a comparison between the significance of the explored packages is presented in Figure 4.25. The ground and upper floor construction package was the most significant across both projects, on average representing 43% of total initial embodied energy consumption. Despite the diversity between the actual measured values (i.e. energy consumption) for the packages, the relative impact per building area for both projects were similar; 6.5 GJ/m^2 for Project 1 and 6.9 GJ/m^2 for Project 2. In addition, the relative significance and the relative impact per building area for the frame construction packages were similar. Evidently, only a few construction packages were explored within Project 3, especially as the earthworks and groundworks packages were procured by the same sub-contractor. The frame was the most significant construction package overall, responsible for 84% of total initial embodied energy. However, this construction package was procured by two different sub-contractors by using two different construction methods and associated materials. The sub-structure derived from a reinforced concrete (RC) frame (four floors) which included reinforced concrete floors whereas the superstructure contained a steel frame (eleven floors) which included metal deck floors (topped with concrete), all of which was tied into two RC frame cores. The RC and steel frames were responsible for 20% and 64% of the total initial embodied energy consumption

respectively. Interestingly the type of foundations used across each construction project varied which influenced their respective impact and significance per project. In terms of total initial embodied energy consumption, the vibro-compaction piles (i.e. aggregates) used in Project 1 were responsible for 0.1% ($6.63x10^1$), the driven piles (i.e. pre-cast concrete) used within Project 2 were responsible for 2.3% ($1.35x10^4$), whereas the bored piles (i.e. in-situ concrete) used within Project 3 were responsible for 9.0% ($2.65\ x10^4$). Evidently changing foundation design and materials used would help reduce total impacts, though the RE recognised the selected foundation type per project was dependent upon ground conditions and the formation (and loading) of the intended building.

Table 4.55 Total initial embodied energy consumption per construction package per construction project

Total EE per	**Project 1**		**Project 2**		**Project 3**	
Construction Package	Value	Sig.	Value	Sig.	Value	Sig.
Cold Store Walls	3.68E+03	2.9	-	-	-	-
Dock Levellers	6.34E+02	0.5	3.46E+04	5.8	-	-
Earthworks	2.72E+03	2.1	1.32E+04	2.2	(inc. Groundworks)	
Electrical / Mechanical	2.50E+03	2.0	1.09E+04	1.8	-	-
External Slab	2.31E+04	18.2	7.54E+04	12.7	-	-
External Walls / Roof	7.36E+03	5.8	5.40E+04	9.1	-	-
Foundations	6.63E+01	0.1	1.35E+04	2.3	2.65E+04	9.0
Frame	1.67E+04	13.2	7.35E+04	12.4	2.49E+05	84.3
Ground & Upper Floor	5.74E+04	45.3	2.45E+05	41.3	(inc. Frame)	-
Groundworks	3.96E+03	3.1	2.15E+04	3.6	1.88E+04	6.4
Internal Walls	1.59E+02	0.1	4.94E+02	0.1	-	-
Main Contractor	1.01E+03	0.8	2.83E+03	0.5	1.20E+03	0.4
Racking	5.49E+03	4.3	3.98E+04	6.7	-	-
Refrigeration	5.82E+01	0.0	-	-	-	-
Retaining Walls	4.55E+02	0.4	1.97E+03	0.3	-	-
Sprinklers	1.29E+03	1.0	5.81E+03	1.0	-	-
Syphonic Drainage	1.65E+01	0.0	3.25E+02	0.1	-	-
Total	**1.27E+05**	**100**	**5.93E+05**	**100**	**2.96E+05**	**100**

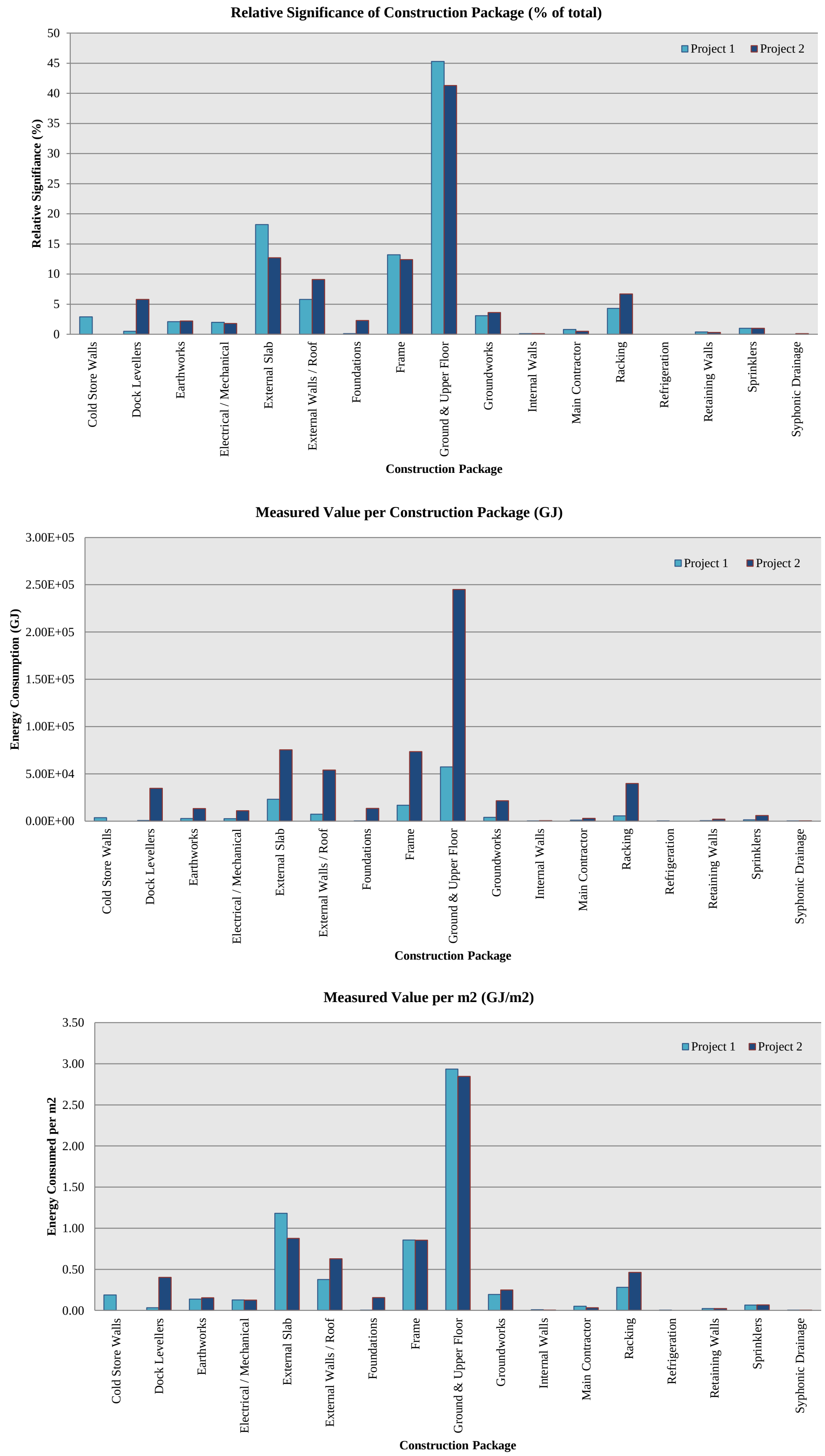


Figure 4.25 Comparison between the explored construction packages within Project 1 and 2

Table 4.56 compares the significance of material phase energy relative to building area for each explored construction project. Notably the relative significance of each of the material phase energy per construction package was similar to the overall relative significance values (i.e. in relation to total initial embodied energy consumption) presented previously in Table 4.55; due to the overwhelming significance of material phase energy (Table 4.59). Figure 4.26 illustrates the actual measured values (i.e. material phase energy) across each construction project. Despite major differences, the ground and upper floor and frame construction packages for Project 2 and 3 respectively produced overall similar results. In terms of material phase energy, the racking construction package (i.e. metal racking for material storage) within Project 2 was 86% greater in comparison to the racking package in Project 1. The RE recognised this was primarily due to the overall size of the building area, as once normalised, the values were similar across both projects. Furthermore, the overall material phase energy per building area was similar across Project 1 and 2 were similar; 6.31 GJ/m^2 and 6.50 GJ/m^2 respectively. The overall results highlight the importance of steel and concrete-based materials within the following construction packages: frame, upper and ground floor, external slab, racking and dock levellers.

Table 4.56 Comparison of material phase energy relative to building area per construction project

Total MAT EE per Construction Package	Project 1 (GJ/m^2)	Sig.	Project 2 (GJ/m^2)	Sig.	Project 3 (GJ/m^2)	Sig.
Cold Store Walls	1.88E-01	3.0	0.00E+00	0.0	0.00E+00	0.0
Dock Levellers	3.22E-02	0.5	3.93E-01	6.1	0.00E+00	0.0
Earthworks	1.31E-01	2.1	7.17E-02	1.1	0.00E+00	
Electrical / Mechanical	1.06E-01	1.7	9.61E-02	1.5	0.00E+00	0.0
External Slab	1.18E+00	18.7	8.67E-01	13.3	0.00E+00	0.0
External Walls / Roof	3.74E-01	5.9	5.76E-01	8.9	0.00E+00	0.0
Foundations	2.97E-03	0.0	1.43E-01	2.2	5.09E-01	9.1
Frame	8.52E-01	13.5	8.34E-01	12.8	4.77E+00	85.1
Ground & Upper Floor	2.93E+00	46.4	2.83E+00	43.6	0.00E+00	0.0
Groundworks	1.36E-01	2.2	1.58E-01	2.4	3.29E-01	5.9
Internal Walls	8.05E-03	0.1	3.86E-03	0.1	0.00E+00	0.0
Main Contractor	0.00E+00	0.0	0.00E+00	0.0	0.00E+00	0.0
Racking	2.81E-01	4.4	4.44E-01	6.8	0.00E+00	0.0
Refrigeration	1.93E-03	0.0	0.00E+00	0.0	0.00E+00	0.0
Retaining Walls	2.30E-02	0.4	1.89E-02	0.3	0.00E+00	0.0
Sprinklers	6.53E-02	1.0	5.83E-02	0.9	0.00E+00	0.0
Syphonic Drainage	6.21E-04	0.0	5.30E-04	0.0	0.00E+00	0.0
Total (GJ/m^2)	6.31E+00	100.0	6.50E+00	100.0	5.60E+00	100.0

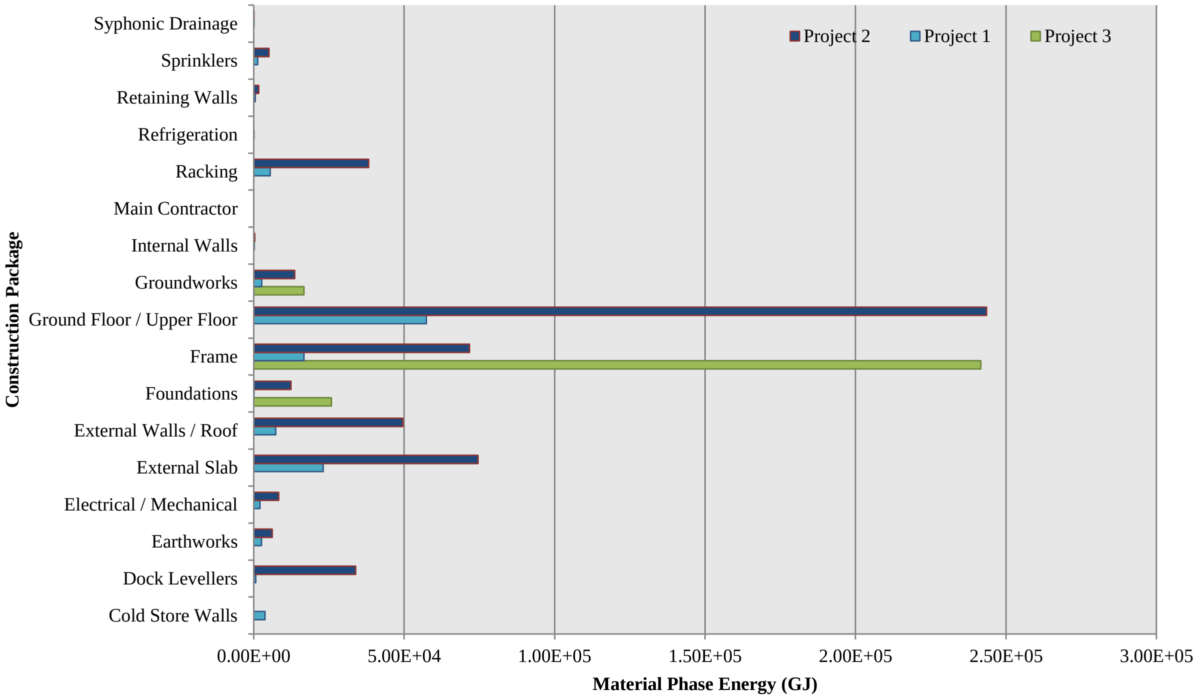


Figure 4.26 Comparison between total material phase energy per construction package for each construction project

Table 4.57 compares the significance of transportation phase energy for each explored construction project. As noted previously, limited transportation phase impacts were captured within Project 1 whereby only the contractor's plant and equipment movements (i.e. site cabins, fuel deliveries and waste skip movements) was assessed. In terms of Project 2, the transportation of materials (mainly the external walls and roof material) was responsible for the largest proportion of total transportation phase energy (64%), though this was less significant for Project 3 (28%). Primarily this outcome was due to the difference in the average distance travelled per delivery of plant and equipment; for Project 2 and 3 the average distances were 113 km and 54 km respectively. With regards to the foundation package, the findings suggested it was 50% more energy intensive to transport the pre-cast piles for Project 2 and the in-situ concrete used for the bored piles within Project 3. The transportation of plant and equipment was significant for Project 3 and responsible for 41% of total transportation phase energy. Primarily this was due to the 676 waste skip movements (i.e. removal of soil) which occurred during the initial stage of the earthworks and groundworks construction package. These movements were responsible for 97% of the total plant and equipment transportation impacts. The average distance of waste skip movements varied across the projects, whereby this distance was 19 km, 16 km and 68 km for Projects 1, 2 and 3 respectively. The relative significance of operative movements was the same for both Project 2 and 3 (i.e. 31%) despite differences within average number of operatives per day; 101 for Project 2 and 86 for Project 3.

Table 4.57 Comparison between transportation phase impacts relative to project resource per construction project

Total TRAN EE per Construction Package	Project 1			Project 2			Project 3		
	Materials	P&E[a]	Operatives	Materials	P&E[a]	Operatives	Materials	P&E[a]	Operatives
Cold Store Walls	-	-	-	-	-	-	-	-	-
Dock Levellers	-	-	-	4.85E+02	2.52E+01	2.13E+02	-	-	-
Earthworks	-	-	-	0.00E+00	9.44E+01	4.37E+02	-	-	-
Electrical / Mechanical	-	-	-	1.02E+02	4.80E+01	3.89E+02	-	-	-
External Slab	-	-	-	6.05E+02	1.60E+01	2.45E+02	-	-	-
External Walls / Roof	-	-	-	3.45E+03	6.24E+01	5.20E+02	-	-	-
Foundations	-	-	-	6.96E+02	2.16E+01	4.04E+01	2.93E+02	3.50E+01	4.95E+01
Frame	-	-	-	8.60E+02	6.30E+01	1.65E+02	1.77E+03	1.99E+03	1.73E+03
Ground & Upper Floor	-	-	-	5.08E+02	4.79E+01	1.98E+02	-	-	-
Groundworks	-	-	-	6.95E+02	8.82E+01	9.80E+02	2.55E+02	1.16E+03	2.78E+02
Internal Walls			-	7.13E+01	4.23E+00	6.88E+01			
Main Contractor	-	5.18E+02	-	0.00E+00	1.61E+02	7.20E+02	-	1.89E+02	4.70E+02
Racking	-	-	-	1.09E+03	6.08E+01	3.98E+02	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-
Retaining Walls	-	-	-	2.31E+02	8.73E+00	7.73E+01	-	-	-
Sprinklers	-	-	-	5.71E+02	2.86E+01	6.88E+01	-	-	-
Syphonic Drainage	-	-	-	5.94E+01	1.48E+01	4.74E+01	-	-	-
Totals (GJ)	0.00E+00	5.18E+02	0.00E+00	9.42E+03	7.45E+02	4.57E+03	2.32E+03	3.37E+03	2.52E+03
Sig. (%)	0	100	0	64	5	31	28	41	31

[a] Totals: P&E, plant and equipment.
[b] Sig.: relative significance of total project resource transportation impact per construction project.

Table 4.58 compares the significance of construction phase energy for each explored construction project. Evidently the significance of construction phase energy (overall and in terms of specific construction packages) varied across the projects, including between Project 1 and 2 despite their similarities (i.e. project type and explored construction packages). Both groundworks construction packages within these projects shared similarity in terms of specific material use and construction activities (e.g. drainage, kerb and edgings and pile caps), though the construction phase impact for Project 2 was 75% greater than Project 1. However, the relative significance in relation to total construction phase energy of the package within Project 2 was only 19% whereas this package represented 44% of total impacts for Project 1. Notably this was due to the significance of the earthworks package within Project 2, as this package consumed more energy than the total construction phase energy for Project 1 and 3 combined. Specifically the earthworks package took 25 weeks (125 business days) to complete whereby the associated plant-intensive construction activities (i.e. site cut and fill exercise using the reprocessed aggregate material derived from the original building) consumed 166,589 litres of red diesel. In terms of Project 3, a combination of red diesel and electrical energy was used to power on-site operations. Moreover, the frame construction package consumed 98% and 64% more on-site energy than the associated packages within Project 1 and 2 respectively. Though, as previously highlighted, the RE recognised that the overall scope of the frame package within Project 3 (i.e. RC frame and steel frame) was significantly different than for Project 1 or 2 (i.e. steel frame). With regards to the foundation package, the findings revealed the installation of the bored piles consumed 98% more on-site energy than the vibro-compaction piles used within Project 1, though 16% less than the driven piles used within Project 2.

Table 4.58 Comparison between construction phase energy per construction project

Total CON EE per Construction Package	Project 1 (GJ)	Sig.[a]	Project 2 (GJ)	Sig.[a]	Project 3 (GJ)	Sig.[a]
Cold Store Walls	2.28E+00	0.2	-	0.0	-	0.0
Dock Levellers	3.32E+00	0.2	6.70E+01	0.5	-	0.0
Earthworks	1.48E+02	10.3	6.52E+03	47.0	-	
Electrical / Mechanical	5.64E+00	0.4	2.56E+02	1.8	-	0.0
External Slab	5.82E-01	0.0	4.45E+01	0.3	-	0.0
External Walls / Roof	3.70E+01	2.6	4.19E+02	3.0	-	0.0
Foundations	8.19E+00	0.6	4.12E+02	3.0	3.48E+02	10.6
Frame	4.41E+01	3.1	6.82E+02	4.9	1.92E+03	58.2
Ground & Upper Floor	1.88E+01	1.3	4.89E+02	3.5	-	0.0
Groundworks	6.34E+02	44.0	2.58E+03	18.6	4.88E+02	14.8
Internal Walls	1.20E+00	0.1	1.78E+01	0.1	-	0.0
Main Contractor	4.97E+02	34.5	1.95E+03	14.1	5.41E+02	16.4
Racking	4.52E+00	0.3	1.15E+02	0.8	-	0.0
Refrigeration	1.07E+01	0.7	-	0.0	-	0.0
Retaining Walls	5.29E+00	0.4	1.95E+01	0.1	-	0.0
Sprinklers	1.42E+01	1.0	1.34E+02	1.0	-	0.0
Syphonic Drainage	4.39E+00	0.3	1.57E+02	1.1	-	0.0
Total (GJ)	1.44E+03	100.0	1.39E+04	100.0	3.30E+03	100.0

[a] Sig.: relative significance of each construction phase impact per construction package relative to total construction phase energy.

Table 4.59 compares the significance of individual life cycle phases per explored construction project. Evidently, material phase energy was the most significant phase across each construction project, representing 96.6% of total initial embodied energy consumption on average. In terms of Project 1, as limited transportation phase impacts were captured this further increased the significance of the respective material phase energy. In terms of Project 2 and 3, despite including significant differences in terms of project type, timescale and explored construction packages, the respective transportation phase impacts were similar. In contrast, the significance of construction phase energy within Project 2 and 3 was dissimilar representing 2.3% and 1.1% of the total respectively.

Table 4.59 Comparison between total initial embodied energy per life cycle phase per construction project

Total EE Life Cycle Phase	Project 1	Project 2	Project 3
Material Phase (GJ)	1.38E+05 (±4.40E+04)[a]	5.75E+05 (±2.30E+05)[b]	3.69E+05 (±1.48E+05)[c]
Sig.	98.5%	95.2%	96.1%
Transportation Phase	5.70E+02 (±1.82E+02)[a]	1.52E+04 (±6.07E+03)[b]	1.07E+04 (±4.27E+03)[c]
Sig.	0.4%	2.5%	2.8%
Construction Phase (GJ)	1.58E+03 (±5.07E+02)[a]	1.43E+04 (±5.71E+03)[b]	4.28E+03 (±1.71E+03)[c]
Sig.	1.1%	2.3%	1.1%
Total EE	1.40E+05 (±4.47E+04)[a]	6.05E+05 (±2.42E+05)[b]	3.84E+05 (±1.54E+05)[c]

[a] Life Cycle Phase Totals: totals includes measured values plus additional 10% for non-reporting scope.
[b] Life Cycle Phase Totals: totals includes measured values plus additional 3% for non-reporting scope.
[c] Life Cycle Phase Totals: totals includes measured values plus additional 30% for non-reporting scope.
[d] Life Cycle Phase Totals: totals represent the measured value, the ±% error (± error value)

Table 4.60 illustrates the amount of material waste consumed by each explored construction project. As noted previously (section 3.2.3) waste consumption was examined by the RE when data was made available and presented within the contractor's SWMP. In terms of Project 1, the volume of total waste produced was derived from literature, as a large proportion of data was missing from the respective SWMP. In terms of Project 2 and 3, the total volume of waste produced was 76% less and 14% less than the estimated waste consumption from literature respectively. The large variation between the estimated and reported waste volume for Project 2 highlights the importance of capturing relevant primary data (in this case waste data) than using historic secondary data to evaluate the performance of a specific construction project. Nonetheless, as stated previously (section 3.4) these reported values contain a high degree of uncertainty as only mixed waste was captured (i.e. waste streams were not fully segregated) within the SWMP and the evidence in literature did not provide estimated waste volumes for excavation works (i.e. removal of soil).

Table 4.60 Comparison between total waste consumption and corresponding material phase energy per construction project

Total Waste Consumption[e]	Project 1	Project 2	Project 3
Building Area	19,564 m^2	86,000 m^2	50,700 m^2
Material Phase	1.29E+05 GJ	5.75E+05 GJ	3.69E+05 GJ
Waste Energy	5.96 E+04 GJ	6.02E+04 GJ	1.56 E+05 GJ
Material Phase Sig. [c]	46%	10%	42%
Waste Volume Estimated	2.17E+03[a] m^3	9.30E+03[a] m^3	5.83E+03[a] m^3
Waste Volume Captured	2.17E+03[a] m^3	2.20E+03[b] m^3	5.04E+04[b] m^3
Waste Volume Sig. [d]	same	76% less	14% less

[a] Waste Totals: waste total derived from literature (i.e. estimated value based upon project type).
[b] Waste Totals: waste total derived from contractor's SWMP (mixed values reported only).
[c] Material Phase Sig.: relative significance (proportion) between material phase energy and waste consumption energy.
[d] Waste Volume Sig.: relative significance (proportion) between estimated and captured waste volume.
[e] Totals: all values linked to Table 4.59.

4.7.2 Practical Challenges

Many practical challenges for addressing initial embodied energy consumption were identified as a consequence of the research project, which were highlighted within the previous research cycles and corresponding research papers (Appendix A to Appendix D). Primarily, the RE recognised challenges relating to the capture, normalisation and organisation of data currently inhibit the overall awareness and assessment of initial embodied energy consumption within construction projects. Comprehending and potentially overcoming these challenges would help the contractor target potential reductions within future projects.

4.7.2.1 Capturing Data

Table 4.61 summarises the difficulties emerged from capturing detailed primary and secondary data from both historic and live construction projects. The potential for historic EPI data to support construction phase energy prediction within future projects was identified. Although, a significant proportion of variability in results was accounted for by other project variables not captured within the EPI procedure (paper 1). Evidently, the type and level of data captured within the procedure did not truly reflect how or why energy was consumed during project development. In addition unknowns and inconsistencies within historic data question the validity of the overall procedure to truly reflect construction phase energy performance and whether data was effectively reviewed by contractor operatives across various reporting levels (i.e. Director, Operations, and Project Level). Furthermore, capturing and linking material data between the contractor current practices (e.g. bill of quantities, design drawings) and the embodied energy coefficients within the ICE material database proved difficult as data was highlighted in various inconsistent forms (i.e. weight per unit, weight of total, length, kg/m^2) which required to be converted into a common format before computation; highlighting the need for further standardisation of units for environmental measurement (BIS, 2010; Carbon Connect, 2011) (paper 4). Capturing transportation data from contractor current practices (e.g. sign-in sheets) and the embodied energy coefficients within the Defra Guide was also difficult as data was revealed as incomplete and incoherent (paper 3). Evidently, the validity of these data sources and others to truly reflect the environmental impacts can be questioned if founded upon secondary sourced data and narrow system boundaries. As a result of these difficulties, certain data assumptions were required to overcome gaps in data, which caused a degree of uncertainty surrounded the overall captured data and results obtained from the explored construction projects. Notably within Project 2, the RE estimated that the significance of transportation phase impacts varied from 1.1% to 5.5% of total initial embodied energy consumption due to the uncertainty within the captured data. Nonetheless, due to the lack of existing available robust data surrounding the topic, evidence within industry literature suggested it is more important to reduce environmental impacts associated with construction projects than necessitate on the overall accuracy of results (RICS, 2012; HM Treasury, 2013). In particular, there is a need for project stakeholders (i.e. manufactures and supply chain) to improve understanding and information on material phase impacts whereby the recent development of the CEN TC 350 Standards, the WRAP embodied carbon database for buildings and improvements to Environmental Product Declarations (EPD's) for construction materials could potentially fulfil this requirement (BIS, 2010; Halcrow Yolles, 2010; WRAP, 2015b; WRAP, 2015c).

Table 4.61 Challenges for data capture during the five research cycles

Data Type	Challenge[a]
Primary Sourced	- EPI data did not accurately reflect how or why energy was consumed during project development; - EPI data was deemed irrelevant factor towards project success; - PoW data had no reference to sub-contractors; - Plant register data varied in terms of content, detail, legibility and terminology; - Plant register data had no reference between project resource and sub-contractor per construction activity; - BoQ and design drawings data was displayed in no consistent format; - Sign-in sheet data varied in terms of content and accuracy; - Form 'A', 'B' and 'C' data varied in terms of content, detail, legibility and terminology.
Secondary Sourced	- EPI data contained significant variability; - LCA data contained limited reference to transportation and construction phase impacts; - LCA data did not reference key parameters; - ICE material database relied upon historic data with narrow system boundaries.

[a] Challenge: EPI, Environmental Performance Indicator procedure; PoW, Programme of Works; BoQ, Bill of Quantities; LCA, Life Cycle Assessment data from previous studies; ICE, Inventory of Carbon and Energy; Form 'A','B','C', New Sign-in Sheets.

Capturing data per sub-contractor and construction package was intended to improve the awareness and management of initial embodied energy consumption within the contractor in terms of identifying project specific significant contributors (i.e. 'hot spots') and aligning data requirements within current practices (i.e. BoQ) and forms of environmental measurement (i.e. BREEAM) to potentially help set targets and drive focused energy consumption reduction within future projects. However, on occasion the RE recognised difficulties in terms of linking specific construction activities to construction packages (paper 3) and differentiating the significance of certain life cycle phases (e.g. construction phase energy) when two or more construction packages were procured by the same sub-contractor (i.e. used and shared the same project resources) (paper 4). Nonetheless, despite the apparent difficulty, capturing data in terms of individual life cycle phases (e.g. material phase) and specific construction packages can further improve understanding of the potential outcomes that can occur from changes in initial embodied energy consumption derived from project resource (i.e. material, plant and equipment, operatives) and construction method selection.

4.7.2.2 Normalising Data

Many existing forms of environmental measurement (e.g. Simplified Building Energy Model, Environmental Performance Certificate, BREEAM, Carbon Profiling) normalise operational energy performance relative to building area (BICS, 2006; BIS, 2010; BREEAM, 2011; DECC, 2009a; RICS, 2010). However, the RE acknowledged that applying this approach towards initial embodied energy consumption could misrepresent results and consequently overlook the significance of project type (e.g. industrial warehouse, multi-storey office) and site area. A sample of twenty-four new-build education and healthcare projects (i.e. colleges, schools, universities and hospitals) were explored within research cycle 1. The ‘Project Type’ specific modelled equations derived from the sample reflected more accurate results in comparison to the ‘All Projects’ modelled equations towards predicting on-site energy consumption performance (paper 1). Two industrial warehouse projects were explored within research cycles 3 and 4 (i.e. Project 1 and 2). Both projects were designed for the delivery and storage of grocery retail products; hence a significant proportion of their site area (approximately 57%) was taken up by hard landscaping (i.e. kerbs, edges, road infrastructure, pathways, and delivery and loading bays). Consideration towards total site area, as opposed to just building area, enabled the impact from additional construction activities and packages (i.e. external slab, earthworks, groundworks and main contractor) to be captured. Table 4.62 reflects the comparison between the initial embodied energy consumption derived from the building area (i.e. building footprint) and external area (i.e. difference in area between site and building) discovered from Project 1 and 2. Evidently, the impact derived within the external area for the external slab, earthworks, groundworks and main contractor packages represented

22% and 16% of total initial embodied energy consumption within Project 1 and 2 respectively. Nonetheless in contrast, within Project 3 a multi-storey commercial office was explored which was located within a dense, urban environment (i.e. surrounded by road infrastructure, pathways, and buildings), thus the project contained no additional site area beyond the original building footprint. Typically impacts derived from the site area have been overlooked previously within industry literature, although improved consideration towards both project type and site area can help improve understanding of a project's true value in terms of initial embodied energy consumption and to create more meaningful benchmarks and targets for project stakeholders to drive reduced initial energy consumption within future projects.

Table 4.62 Comparison between initial embodied energy consumption considering building and external area within construction projects 1 and 2

Construction Packages	Project 1[a]			Project 2[b]		
	Total EE for site area (GJ)	Total EE for building area (GJ)[c]	Total EE for external area (GJ)[d]	Total EE for site area (GJ)	Total EE for building area (GJ)[e]	Total EE for external area (GJ)[f]
Main Contractor	1.01E+03	4.32E+02	5.83E+02	2.83E+03	1.24E+03	1.59E+03
Earthworks	2.72E+03	1.16E+03	1.56E+03	1.32E+04	5.79E+03	7.43E+03
Groundworks[f]	3.30E+03	1.40E+03	1.89E+03	1.79E+04	7.85E+03	1.01E+04
External Slab	2.31E+04		2.31E+04	7.54E+04		7.54E+04
Total (Selected)[g]	3.01E+04	2.99E+03	2.71E+04	1.09E+05	1.49E+04	9.45E+04
Total (Remaining)[g]	9.54E+04			4.78E+05		
Total (All)[g]	1.25E+05			5.87E+05		
% of Total (All)[g]	100%	2%	22%	100%	3%	16%

[a] Calculation: Project 1, Site area, 45,973 m^2; Building area, 19,564 m^2; External area, 26,409 m^2 (site area – building area)
[b] Calculation: Project 2, Site area, 191,074 m^2; Building area, 83,675 m^2; External area, 107,399 m^2 (site area – building area)
[c] Calculation: Project 1, Total EE for site area x 42.6% (proportion of EE relative to building area)
[d] Calculation: Project 1, Total EE for site area x 57.4% (proportion of EE relative to external area)
[e] Calculation: Project 2, Total EE for site area x 43.8% (proportion of EE relative to building area)
[f] Calculation: Project 2, Total EE for site area x 56.2% (proportion of EE relative to external area)
[g] Calculation: Total (Selected), EE from selected construction packages; Total (Remaining), EE from remaining construction packages; Total (All), EE from all construction packages which does not include the additional 20% for scope gaps (e.g. mechanical and electrical package).
[f] Groundworks: Value do not include the additional 20% for scope gaps.

4.7.2.3 Organising Data

The RE recognised during the first research cycle that contractor operatives supported the need for improved and linked project data throughout the contractor's current practices to improve awareness and management of initial embodied energy consumption, in particular construction phase energy, within future construction projects (paper 1). Although, as noted previously, linking construction activities, packages and sub-contractors with associated project resources across individual initial embodied energy phases within a live construction project proved difficult. It was revealed within research cycles 2 and 3 that the majority of existing contractor current practices (e.g. BoQ, design drawings, plant register) organised data per sub-contractor (paper 2 and 3). Hence, research cycle 4 explored the potential for organising data per construction activity and package (as well as sub-contractor) through the revised framework and alternative current practices. The development of the framework did affirm the usefulness of current practices to support an initial embodied energy assessment whereby changes were made to increase the granularity of captured data through enhanced data organisation. The new sign-in sheets developed during research cycle 4 helped to improve the organisation of data in line with the requirements of the revised framework (i.e. capture data per project indicator). In particular, Form ‘C’ provided a fundamental link within the revised framework between transportation and construction phase data per construction activity for each sub-contractor (paper 4). However, data captured from the sub-contractors was either incomplete or varied in terms of content, detail and terminology. Hence, it was not possible to evaluate the impacts for all construction activities. In addition, from the responses alone, it proved difficult to link each construction activity on the programme of works (PoW) to each sub-contractor. Primarily this was due to the contractor needing to react to unforeseen circumstances during the construction phase (i.e. changes in design, materials, construction methods and techniques) which ultimately impacted on the number and duration of many construction packages and activities; consequently the PoW was updated regularly. Furthermore, during instances where no or incomplete responses were received from sub-contractors, the contractor was required to verbally confirm the outstanding data and provide the necessary links. Hence, the RE recognised improved consideration towards autonomous methods of data capture and organisation (as used within research cycle 5 to capture transportation movements) can reduce reliance upon contractor operative's being required to monitor and manage the data capture and organisation process.

4.7.3 Practical Opportunities

Many practical opportunities for addressing initial embodied energy consumption were identified as a consequence of the research project, which were highlighted within the previous research cycles and corresponding research papers (Appendix A to Appendix D). Primarily, the RE recognised these opportunities related to individual material, transportation, and construction phases and overall project life cycle energy consumption. Acknowledging and potentially exploiting these opportunities would help the contractor target potential reductions within future projects.

4.7.3.1 Material Phase Energy

The significance of material phase energy was consistent across the three explored construction projects. Specifically, material phase energy accounted for 98.5%, 95.1% and 96.1% of total initial embodied energy consumption within Projects 1, 2 and 3 respectively. Hence, the RE recognised that primarily efforts by contractors to reduce initial embodied energy consumption should be directed towards reducing material phase energy. The importance of using recycled material to help reduce material phase energy was recognised previously within industry literature (Harris, 1999; Chen et al., 2001; Rai et al., 2011) and in practice within Project 2, as recycled aggregates were used in place of virgin aggregates to support the earthworks construction package (due to initial demolition works), which resulted in an energy saving of 6.16×10^3 GJ (50%). Table 4.63 displays a simple comparison between material alternatives for the frame construction packages across the explored construction projects. In this instance, using a timber frame as opposed to a steel frame within Project 1 or

2 would have potentially reduced the associated material phase impact by 97%. However, limited awareness surrounds the potential outcomes which may emerge from undertaking such a simple narrow approach, especially as material quantities, characteristics and performance criteria are important (paper 4). Significant energy savings could have been achieved within Project 2 through the selection of alternative concrete mix design; substituting steel fibre-reinforcement concrete with traditional in-situ concrete with steel reinforcement. Consequently, the material phase impact associated with the ground and upper floor package could have reduced by 73%. However, it was found that the concrete mix design was selected as it allowed the contractor to include an additional rapid hardening agent which reduced concrete curing time and allowed other construction packages (e.g. sprinklers and syphonic drainage packages) to commence work shortly afterwards. Evidently, the impact on project procurement and delivery needs to be considered when selecting material alternatives.

Table 4.63 Comparison between material substitutions for the frame construction package across construction project's 1, 2 and 3

			Material Substitutions		
No.[a]	**Construction Package[a]**	**Existing Material (MJ)[b]**	**Timber (MJ)[b]**	**Reinforced Concrete (MJ)[b]**	**Steel (MJ)[b]**
3	**Steel Frame[c]**	1.67E+07	4.99E+05	3.63E+05	
	(% Change[g])		(97% decrease)	(98% decrease)	
4	**Steel Frame[d]**	7.17E+07	2.15E+06	1.56E+06	
	(% Change[g])		(97% decrease)	(98% decrease)	
5	**RC Frame[e]**	3.27E+07	4.49E+07	-	1.85E+09
	Steel Frame[f]	1.43E+08	3.47E+06	2.52E+06	1.43E+08
	(% Change[g])		(72% decrease)	(78% decrease)	(1,033% increase)

[a] No.: Case Study number (Case Study 3, 4 or 5); RC, reinforced concrete.
[b] Calculation: Density of steel, 7,800 kg/m^3; Density of reinforced concrete, 2,400 kg/m^3; Density of timber, 720 kg/m^3; Embodied energy coefficient for steel, 35.30 MJ/kg (for case study 5 only); Embodied energy coefficient for steel, 28.67 MJ/kg; Embodied energy coefficient for reinforced concrete, 2.03 MJ/kg; Embodied energy coefficient for timber, 9.30 MJ/kg.
[c] Calculation: Volume of steel, reinforced concrete and timber, 74.53 m^3.
[d] Calculation: Volume of steel, reinforced concrete and timber, 320.61 m^3.
[e] Calculation: Volume of reinforced concrete, 6,701.60 m^3 (same for steel and timber). RC frame located between level two and roof.
[f] Calculation: Volume of steel, 518.20 m^3 (same for reinforced concrete and timber).
[g] % Change: Difference in value between existing material total and substitution material total.

In addition to material selection, the importance of waste consumption was also highlighted within the research cycles. The RE discovered that material waste consumption was responsible for an additional 46%, 10% and 42% of material phase energy for Project 1, 2 and 3 respectively. The RE recognised that material waste did not only influence material phase energy through increased material manufacture, but also transportation phase energy through increased transportation of waste material off-site, and increased construction phase energy through increased management of waste material on-site (i.e. moving and segregating waste via plant and equipment). Evidently, to make significant reductions within initial embodied energy, the contractor should provide targets and incentives to sub-contractors and the wider supply chain to reduce waste consumption during construction and design out waste pre-construction through options such as increased reliance upon offsite manufacture, reduced material packaging, and improved uptake of material 'take-back schemes' (i.e. waste material taken back and used by manufacturer to offset virgin material) (BRE, 2015b).

4.7.3.2 Transportation Phase Energy

The importance of using locally sourced project resources was apparent. Each explored project was located within the south of England near many road and rail transportation links, which provided project teams with many sourcing options especially for materials. Table 4.64 compares the number of deliveries and distance travelled for the locally sourced in-situ concrete within Projects 2 and 3. In-situ concrete was the only material sourced less than 40 km to site for both Projects. With regards to Project 2, despite in-situ concrete deliveries representing 82% of the total number of deliveries, these deliveries only signified 12% of the total transportation phase energy related to material movement. In contrast, 357 deliveries of external walls and roof insulation were sourced over 330 km which represented 37% of the total impact (paper 4). The RE acknowledged contractors could experience significant environmental and cost benefits from using locally sourced materials, fuel efficient vehicles, prefabricated building elements and using consolidation centres to increase delivery reliability. Although, as transportation phase impacts are site specific, this makes it difficult to highlight significant trends across different projects types and locations.

Table 4.64 Comparison of locally sourced in-situ concrete for construction projects 2 and 3

	Project 2		**Project 3**	
Construction Package (in-situ concrete)	Total Number of Deliveries	Distance Travelled (km)[a]	Total Number of Deliveries	Distance Travelled (km)[a]
Foundations	-	-	687	17
Groundworks[b]	157	10	560	17
RC Frame[b]	-	-	1,915	17
External (Slab)	2,561	10	-	-
Ground and Upper Floor (Slab)	2,149	10	-	-
Total Number of Deliveries	4,867	-	3,162	-
Total Distance Travelled	-	93,992	-	53,754
% of Total Project[c]	**82%**	**14%**	**97%**	**61%**
% of Total Embodied Impact[d]	**-**	**12%**	**-**	**57%**

[a] Distance Travelled: Distance to site only.
[b] Construction Package: Groundworks, includes Earthworks package; RC, reinforced concrete.
[c] % of Total Project: Total number of deliveries for total project 5,975 (Project 2) and 3,248 (Project 3); Total distance travelled for total project to and from site 676,021 km (Project 2) and 176,252 km (Project 3).
[d] % of Total Embodied Impact: Embodied impact relating to total project energy derived from the transportation of materials.

4.7.3.3 Construction Phase Energy

A lack of existing, robust data and emphasis towards construction phase energy within previous research was recognised within industry literature (Smith, 2008; Dixit et al., 2010; Gustavsson et al., 2010). Although, multiple advantages for improved consideration and enhanced data were highlighted by contractor operatives, such as: increased transparency of existing data; formation of future benchmarks; greater appreciation of energy use and best practice; and improved overall competency and competitiveness. The RE acknowledged that the contractor was directly responsible for and can influence energy consumption during construction through the selection of alternative methods of construction, project resources and on-site energy sources. In particular, it was discovered that the contractor used a mixture of red diesel and electrical energy to power on-site operations, though typically red diesel was used to power initial on-site operations, as highlighted within research cycle 1 and 5. The RE acknowledged that this decision was influenced by the high initial capital cost for the main electrical grid supply, the limited lead-in time between obtaining the project contract and starting the on-site construction phase, and the difficulty in agreeing a practical location for the supply that would benefit the temporary on-site accommodation and main building positioning (paper 1 and 4). During research cycle 5, the explored construction project utilised both red diesel and electrical energy from the national grid early on due to existing electrical connections being available adjacent to site.

From the first research cycle, it was discovered that during 2010 to 2011 a total of 0.06 $MtCO_2$ was produced from all of the contractor operations across all sectors, equating to a potential CRC carbon taxation of approximately £720,000. The sample of 24 new-build education and healthcare projects contributed to approximately 5% (0.003 $MtCO_2$, £36,000) of the contractor's overall CRC carbon taxation. Considering these projects only represented 10% of the contractor's workload, significant opportunities to reduce energy and cost could materialise through specifying fuel efficient plant, accommodation and improving on-site logistics and coordination of activities (paper 1). The annual volume of available construction work, its total contribution towards CO_2 emissions, and associated financial burdens all highlight the importance of construction phase energy and the need for contractor's to assess and reduce the associated impacts.

4.7.3.4 Project Life Cycle Energy

Emphasis towards reducing operational energy in contrast to initial embodied energy was apparent within industry literature (DECC, 2009a; BIS, 2010; RICS, 2010) (paper 1). During the fourth research cycle the RE was able to capture initial embodied energy data and predicted operational energy data from Project 2, which as a result, highlighted the importance of project type and building life span with regards to project life cycle energy. Figure 4.27 compares the significance of operational and initial embodied energy consumption. Initial embodied energy data, captured through the revised framework, was compared against operational energy data captured from the building's Simplified Building Energy Model (SBEM), which identified the predicted operational performance per annum. Within previous LCA studies building lifespan can range between 25-75 years (Cole and Kernan, 1996; Gustavsson et al., 2010; Rai et al., 2011; Scheuer et al., 2003), although in this instance due to the project scope and intentions of the client and developer, the contractor confirmed that the building had an expected lifespan (i.e. design life) of 25 years. Hence, on this occasion the initial embodied impact would remain greater than the operational energy impact at the end of the building's life. In particular it would take approximately 31 years and 28 years for the operational impact to exceed the initial embodied energy and carbon impacts respectively. This finding challenges the view that operational energy should be considered before initial embodied energy as it represents the largest share in project life cycle energy (Gustavsson et al., 2010). Also the evidence questions the current direction of industry directives (DECC, 2009b) and the typical agenda of project stakeholders (Sodagar and Fieldson, 2008; Tassou et al., 2011) as both are primarily focused towards reducing operational energy as opposed to total project life cycle energy. Seemingly instead of decisions being undertaken to address specific life cycle phase impacts (i.e. operational energy), the evidence highlights the need for project stakeholders to consider a holistic view towards total project life cycle impacts. Nonetheless, industry literature identified that within project design development, it is common for contractors to be involved within decisions intended to reduce operational energy through the selection of high embodied energy materials (i.e. super-insulated walls and windows) (Huberman and Pearlmutter, 2008; DECC, 2009a; Kneifel, 2010; RICS, 2010). During these occasions, it is the client and building end user that potentially benefits from increased thermal comfort and reduced energy bills at the expense of the contractor and supply chain through increased resources, energy use and carbon taxation. Although in line with the findings, in some instances (e.g. industrial warehouse) it could be more beneficial for all project stakeholders to target reductions in initial embodied energy consumption (e.g. steel and concrete-based materials) than operational energy to provide more meaningful reduction within project life cycle energy and natural resources. However, further consideration towards the impact of recurring embodied energy, the decarbonisation of the UK national grid, and the variation between predicted and actual operational energy consumption would be required as these factors would directly influence the significance and the relationship between both project life cycle phases.

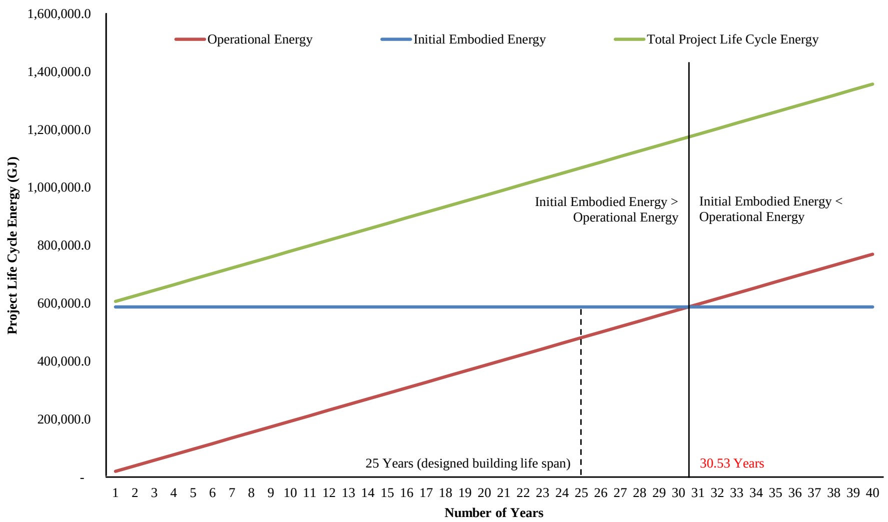


Figure 4.27 Comparison between operational, initial embodied, and total project life cycle energy for construction project 2 (after Davies et al., 2015)

4.7.4 Updated Research Progression

Figure 4.28 illustrates the progression of the research after completion of the fourth overarching objective.

Figure 4.28 Research progress at completion of the fourth overarching objective

5 RESEARCH FINDINGS

This chapter presents the key findings with regards to the first four overarching objectives of the research project. Findings derived from the use of the action research methodology based upon a mixed methods research strategy throughout the research cycles are presented.

5.1 The Key Findings of the Research

5.1.1 Overarching Objective One

Industry literature highlighted many available methods to quantify various aspects of sustainable development. The concept of addressing initial embodied energy was deemed not as advanced in comparison to operational energy due to the lack of clear, consistent methods for data capture, in particular with regards to on-site energy monitoring (paper 1). Practitioners mainly used a life cycle assessment (LCA) to address initial embodied energy consumption, though limitations regarding data sensitivity issues and the complex nature of construction projects were recognised. Consideration of key parameters such as the selection of system boundaries, calculation methods and data sources were regarded as important factors for practitioners to define the usefulness and practicality of findings (paper 3). These key parameters were used to form the basis of the practical framework developed as a result of the third overarching objective (below).

Emphasis towards addressing operational energy in contrast to initial embodied energy was apparent throughout the construction industry, which hindered the lack of available initial embodied energy data. In the majority of previous studies, operational energy represented a greater proportion of project life cycle energy in comparison to initial embodied energy. Although in some cases the relative significance of the two project life cycle phases varied significantly for certain project types and locations (paper 3). For instance, initial embodied energy consumption represented 9% of total project life cycle energy for a retail building in Canada, though in contrast this figure was 60% for an apartment building in Israel (Huberman and Pearlmutter, 2008; Van Ooteghem and Xu, 2012). The relative significance of existing LCA studies, which provided a wide range of project life cycle phase data, was reviewed. Evidently, limited studies provided data on individual project life cycle phases. In terms of total project initial embodied energy, transportation and construction phases were considered small (up to 7% and 6% respectively) in comparison to the material phase (up to 98%) for various project types (paper 2 and Table 2.4). The type and source of data used by practitioners to assess initial embodied energy performance was recognised. Data was typically sourced from a mixture of contractor current practices (i.e. bill of quantities, design drawings) and existing datasets (i.e. ICE material database, Defra Guide) (paper 4). Evidently, achieving a reduction in one particular life cycle phase could impact on another as life cycle phases are highly interdependent.

5.1.2 Overarching Objective Two

Eight current practices which the contractor used during the construction phase of a typical project were evaluated in terms of their potential to support an assessment of initial embodied energy within future projects. The material characteristics within the BoQ and design drawings had to be converted before comparison against existing LCA data as these values were displayed in no consistent format (i.e. mm, m, m^2, m^3, tonne, kg). The project resource database provided limited information as there was no mandatory requirement for the project team to use the database, it was simply perceived as a useful tool which could help certain reporting requirements. The plant register included information which varied significantly in terms of content, detail, legibility and terminology, presenting no clear correlation between the plant and equipment used and the specific construction activities undertaken by sub-contractors (paper 2). The EPI procedure contained unclear information surrounding fuel data in terms of quantity of delivery, the date of delivery, and consumption during intervals (paper 1). Both sign-in sheets captured a varied degree of complete, valid information due their respective locations within the contractor's on-site accommodation and emphasis imposed on them by the project team. The PoW provided no direct link between the construction activities and the sub-contractors responsible for their completion. The SWMP contained limited segregated skip information (e.g. timber, metal, plastic, cardboard) reducing the opportunity to correlate waste and associated transportation data to specific construction packages, activities and sub-contractors (paper 3). Evidently each current practice differed in terms of scope, content and application which are presented in Table 5.1.

Table 5.1 Data captured within the contractor's existing current practices (after Davies et al., 2014, paper 3)

		Resource[a]					
Current Practice (i.e.Data Source)	**Purpose**	**M**	**P**	**O**	**Data Relative to…[b]**	**Data Source**	**Frequency of Data Capture**
Bill of quantities (BoQ)	Coordinate project design	✓			Sub-contractor	Sub-contractor	Once (potential revisions)
Design drawings	Coordinate project cost	✓			Sub-contractor	Designers Sub-contractor	Once (potential revisions)
Resource database	Document project resources	✓	✓	✓	Sub-contractor	Sub-contractor	Daily, Weekly or Monthly
Plant register	Document plant and equipment		✓		Sub-contractor	Sub-contractor	Daily, Weekly or Monthly
EPI procedure	Report environmental performance	**No Reference**			Sub-contractor	Sub-contractor	Monthly
Sign-in sheets	Record attendance and movements	✓	✓	✓	Sub-contractor	Sub-contractor	Daily, Weekly or Monthly
Programme of works (PoW)	Coordinate project delivery	**No Reference**			Con' Package	Sub-contractors Contractor	Once (potential revisions)
Site Waste Management Plan (SWMP)	Report waste consumption	✓			Sub-contractor	Sub-contractor	Daily, Weekly or Monthly

[a] Resource: M, Material; P, Plant and Equipment; O, Operative (current practices provides direct reference to resources).
[b] Relative: Project resource data captured within current practice relative to sub-contractor or construction package.

5.1.3 Overarching Objective Three

The practical framework developed to capture and assess initial embodied energy consumption based upon contractor current practices was evaluated through three live construction projects. Issues recognised within the first explored construction project caused a number of changes to be made to the framework and contractor current practices for subsequent projects (paper 3), in order to reduce data gaps and assumptions. Specifically, changes were made to the PoW, plant register, EPI procedure and sign-in sheets. The alternative PoW highlighted sub-contractor responsibility per construction activity and package to improve awareness of data requirements for sub-contractors and the overall project. The alternative plant register combined all plant and equipment data into one simple register to improve coherence of data. Two new check sheets and a pro forma helped to assess the validity and reliability of captured EPI data from sub-contractors. Three new sign-in sheets (Forms 'A', 'B' and 'C') helped to capture and link project data relative to contractor activities, packages and sub-contractors across three life cycle phases (paper 4). Additional changes were made to the EPI procedure and sign-in sheets within the final explored construction project due to changes in working environment (i.e. different current practices, project teams, construction packages).

Despite variation in project type and scope, all explored construction projects recognised the significance of material phase energy in comparison to transportation and construction phases. Evidently, construction packages which relied upon steel and concrete-based materials were most significant within Projects 1 and 2 (papers 3 and 4); which influenced direction towards the project base-build within Project 3. Material phase energy was responsible for 98.5%, 95.2% and 96.1% of total initial embodied energy for Project 1, 2 and 3 respectively. In terms of Project 2 and 3, despite including significant differences in terms of project type, timescale and explored construction packages, the respective transportation phase impacts were similar. In contrast, the significance of construction phase energy was dissimilar representing 2.3% and 1.1% of the total respectively. The upper and ground floor was the most significant construction package within Project 1 and 2, evident due to the function of the buildings (i.e. transportation and storage of goods). The significance of the foundation package varied throughout the projects due to clear differences within design, material used and construction method. In terms of total initial embodied energy consumption, the vibro-compaction piles (i.e. aggregates) used in Project 1 were responsible for 0.1% ($6.63x10^1$), the driven piles (i.e. pre-cast concrete) used within Project 2 were responsible for 2.3% ($1.35x10^4$), whereas the bored piles (i.e. in-situ concrete) used within Project 3 were responsible for 9.0% ($2.65\ x10^4$).

The effectiveness of the practical framework developed within research cycles 3, 4 and 5 was evaluated in terms of the overall reliability and validity of the captured data. The findings derived from each explored construction project were based upon a different reporting scope which was influenced by the ability of the existing and alternative current practices to fulfil the data requirements of the framework. During instances whereby data gaps were identified, data assumptions were required which impacted the overall degree of uncertainty surrounding the findings. For each explored project Figure 5.1 displays the variation in total energy consumption per individual life cycle phase due uncertainty within the measured values (i.e. upper and lower bound limits). Evidently reducing these uncertainties through increased reporting scope and less associated data assumptions would have helped conclude more precise results.

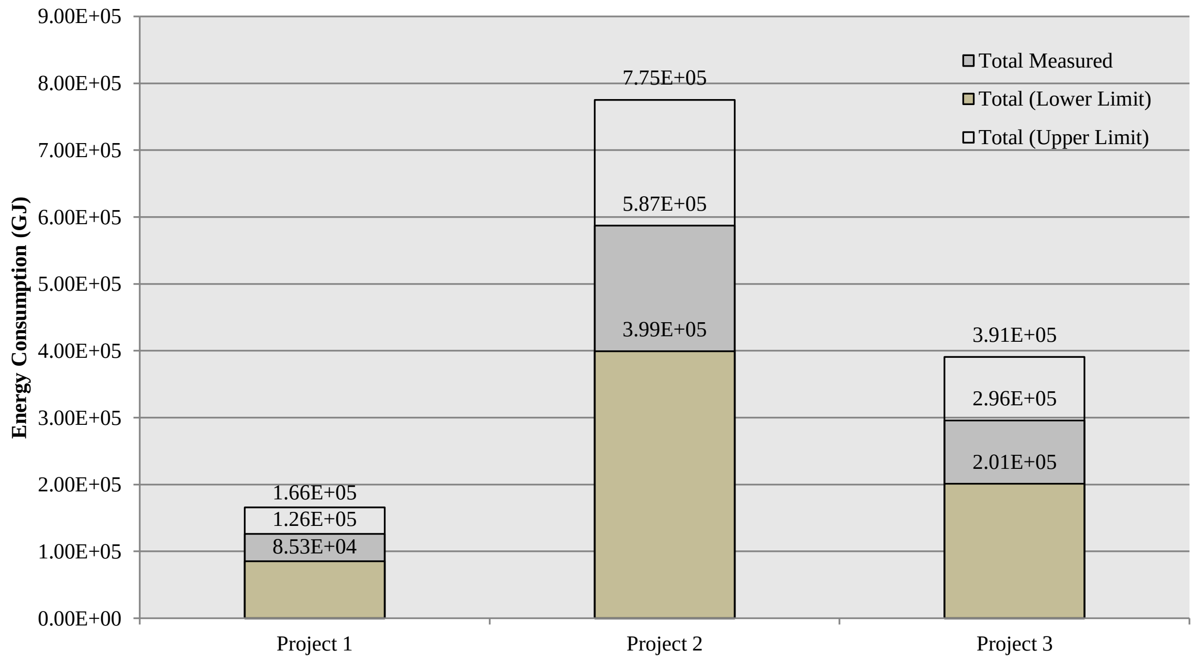


Figure 5.1 Variation within the total initial embodied energy consumption due to uncertainty for construction projects 1, 2 and 3

Within the fifth research cycle, project tender documents form seven large-scale civil engineering and infrastructure projects were reviewed. Consideration and engagement towards initial embodied energy during project development varied between client and contractor information. Clients demonstrated inclination towards reducing material phase energy performance with no reference to transportation or construction phase performance. The scope of the majority of projects emphasised the importance of project cost, planning and the overall capability of the contractor in comparison to an environmental agenda. The contractor highlighted an interest and emphasised the importance of modelling energy or carbon data across different project life cycle phases through BIM, though provided limited practical examples of how this has been applied previously.

5.1.4 Overarching Objective Four

Many practical challenges and for addressing initial embodied energy consumption were identified, primarily relating to the capture, normalisation and organisation of data.

Difficulties emerged from capturing detailed primary and secondary data from both historic and live construction projects. The use of the existing contractor current practices (e.g. sign-in sheets) within Project 1 to capture primary transportation construction data was difficult as data was revealed as incomplete and incoherent (paper 3). The secondary data within the EPI procedure did not truly reflect how or why construction phase energy was consumed during project development. Industry literature highlighted the common approach of normalising operational energy consumption relative to building area. Although it was recognised applying the same approach towards initial embodied energy consumption could misrepresent results. The impacts derived within the external area (i.e. difference in area between site and building) from the external slab, earthworks, groundworks and main contractor packages represented 22% and 16% of total initial embodied energy consumption within Project 1 and 2 respectively (paper 4). Despite contractor operatives recognising the need for linked project data within current practices, linking project data (e.g. construction package data across individual initial embodied energy phases) was difficult as especially as data captured from the sub-contractors was either incomplete or varied in terms of content, detail and terminology.

Many practical opportunities and for addressing initial embodied energy consumption were identified, whereby these opportunities related to individual life cycle phases and overall project life cycle energy consumption. The importance of using recycled material to help reduce material phase energy was recognised as in some instances replacing virgin material with a recycled alternative (i.e. aggregate) reduced overall construction phase impact by 50% (paper 4). Evidently significant material phase energy reductions could have been achieved through selecting an alternative concrete mix design within the upper and ground floor construction package within Project 2. Though, it was recognised that project procurement and delivery needs to be considered when selecting material alternatives. The significance of material waste consumption was also highlighted as this was potentially responsible for an additional 46%, 10% and 42% of material phase energy for Project 1, 2 and 3 respectively. In addition, within Project 2 the importance of using locally sourced project resources was apparent as in-situ concrete deliveries represented 82% of the total number of deliveries but only 12% of the total transportation phase energy related to material movements. Despite the lack of emphasis towards construction phase energy within previous research, as the contractor was deemed directly responsible for and can influence energy consumption during construction, multiple advantages for improved consideration and enhanced data were highlighted such as increased transparency of existing data and formation of future benchmarks. Within Project 2, from evaluating the initial embodied energy data captured by the revised framework and the operational energy data within the building's Simplified Building Energy Model (SBEM) it was discovered that the initial embodied impact would remain greater than the operational energy impact at the end of the building's life. Evidently it was recognised that the finding questions the current direction of industry directives and the typical agenda of project stakeholders, as both are primarily focused towards reducing operational energy as opposed to total project life cycle energy.

6 CONCLUSIONS

This chapter presents the overall conclusion of the research along with the research implications with regards to the industrial sponsor and wider construction industry. The chapter presents the key findings from the final overarching objective of the research project by highlighting a number of recommendations for consideration by contractors and the wider construction industry, along with requirements for future research.

6.1 Overall Conclusion

The thesis presented a four year Engineering Doctorate (EngD) research project into assessing initial embodied energy within UK non-domestic construction projects. An action research methodological approach enabled the assessment and potential reduction of initial embodied energy to be explored through five research cycles which included diagnosing and action planning, action taking, evaluating and specified learning. Table 6.1 illustrates how the research objectives were realised, introduced previously in section 1.4. The subject of initial embodied energy is important to the UK construction industry and economy. Multiple environmental and commercial savings are available for a range of stakeholders including contractors, though further research and development is required. Nonetheless, in terms of assessing initial embodied energy data, previous LCA studies demonstrated limited consistency with regards to data completeness, uncertainty and key parameter selection (i.e. system boundaries, calculation methods, data sources); all of which questions their usefulness to support energy reduction targets within future projects. Contractor current practices provided varied data in terms of detail, legibility, terminology and links between construction packages and corresponding sub-contractors; all of which reduces their efficacy to reflect how or why energy is consumed during different stages of project development. Although the practical framework offers the contractor a more comprehensive approach compared to previous studies towards the capture and assessment of detailed initial embodied energy data from a construction project per construction package with regards to individual life cycle phases. This approach allows the contractor to align data with requirements within existing forms of environmental measurement (e.g. BREEAM), consider impacts commonly overlooked within previous studies (e.g. impacts from outside the building footprint area), develop improved datasets for benchmarking and future reduction targets, and enhance awareness of the significance and relationship between individual life cycle phases. Furthermore, in terms of reducing initial embodied energy consumption, efforts should largely be directed towards tackling material phase energy through the incorporation of recycled and low embodied energy materials during design, and through the efficient use of materials and effective waste reduction strategies during on-site construction. Construction packages which rely upon steel and concrete-based materials (e.g. ground and upper floor, external slab and frame) should be tackled first by project stakeholders. Although selecting alternative materials may impact the contractor in terms of their control over pre-construction and on-site construction activities in particular with regards to the selection of project resources, procurement methods and on-site construction techniques. Contractors can achieve additional reductions through sourcing high embodied energy materials (e.g. concrete) locally and reducing overall reliance upon red diesel fuelled plant-intensive construction activities during construction (e.g. earthworks). Overall, consideration of total project life cycle energy is required when exploring alternative materials or changes to project design; as project stakeholders have different interests and responsibilities within a project life cycle.

Table 6.1 Realisation of the research overarching objectives

Obj. [a]	No.	Sub-objectives (summarised)	Key Findings	Papers[b]
[One]	**1.1**	Review current performance of UK non-domestic sector;	- Significant potential to reduce environmental impact and cost.	**Paper 1**
[One]	**1.2**	Review existing methods for assessing initial embodied energy;	- LCA studies vary in system boundary, calculation method and data source selection.	**Paper 3**
[One]	**1.3**	Review relative significance of	- The significance of initial embodied energy	**Paper 2**

		individual project life cycle phases;	increases as operational energy decreases.	
[One]	**1.4**	Review existing drivers for contractors;	- Carbon taxation through the CRC and the price of energy are significant drivers.	**Paper 1**
[One]	**1.5**	Review existing challenges for contractors;	- Current lack of robust, accurate initial embodied energy data.	**Paper 1**
[One]	**1.6**	Review existing opportunities for contractors;	- Specifying materials with low embodied content and recycled content can reduce impact.	**Paper 1**
[Two]	**2.1**	Investigate the effectiveness of contractor current practices towards managing construction phase energy performance;	- EPI contained ambiguous, incomplete data. - Addition variables are required to improve granularity of EPI data. - Increased target setting skills are required.	**Paper 1**
[Two]	**2.2**	Investigate the potential for contractor current practices to support an initial embodied energy assessment;	- No link between PoW and sub-contractors. - Plant register contained unclear data. - BoQ contained inconsistent data.	**Paper 2**
[Three]	**3.1**	Develop a practical framework;	- No direct relationship between construction activities, packages and sub-contractors.	**Paper 3**
[Three]	**3.2**	Explore the effectiveness of the practical framework;	- Material phase energy deemed significant. - Helped improve contractor current practices.	**Paper 4**
[Four]	**4.1**	Examine the practical challenges and opportunities;	- Challenge to capture detailed, accurate data. - Opportunity to tackle project life cycle energy.	**All Papers**
[Five]	**5.1**	Produce recommendations to address challenges and add value to the opportunities.	- Incentivise reduced initial embodied energy consumption within construction projects. - Address material phase energy and waste.	**All Papers**

[a] Obj: Overarching Objective.
[b] Paper: The main focus of each research paper is aligned to each sub-objective.

As the construction industry moves towards improved operational energy efficiency, initial embodied energy consumption is likely to receive greater consideration within UK government policies and forms of environmental measurement. Contractors can lead the industry towards reduced initial embodied energy consumption due to their significant involvement within project procurement and delivery and access to primary data required for assessment. Contractors which demonstrate practical opportunities to address initial embodied energy consumption are likely to have competitive advantage in future environmentally driven markets, and also be well positioned to influence industry standards and policy strategy. Improved collaborative working across assorted project stakeholders (e.g. clients, designers, sub-contractors) and within internal operations, will allow contractors to develop practical data to support enhanced decision making (e.g. in terms of material selection, transportation strategies, on-site construction methods) intended to reduce initial embodied energy consumption within future projects.

6.2 Implications for the Contractor

The research improved awareness and application of initial embodied energy consumption within construction projects. As a result, the contractor (i.e. industrial sponsor) benefited from the following:

- improved initial embodied energy dataset from recent construction projects;
- improved current practices for capturing and assessing initial embodied energy data;
- improved knowledge of significant contributors towards initial embodied energy consumption;
- improved awareness of the relationship between construction activities, packages and sub-contractors across individual life cycle phases; and
- improved comprehension of the practical challenges and opportunities which influence the assessment and potential reduction of initial embodied energy consumption.

The contractor is now equipped with a simple, cost neutral, practical framework designed to highlight initial embodied energy consumption and potential opportunities to reduce impacts within construction projects (Appendix J). In addition, the development of the framework enabled the contractor to benefit from improvements made to existing current practices, intended to support their on-site operations in terms of enhanced methods for data capture, assessment and verification. The framework demonstrated value in capturing and assessing data within different working environments and project types. Furthermore, the research project provides benefits to the contractor during different project phases. During the project tender phase, the contractor can now demonstrate to clients their awareness, commitment and approach towards addressing initial embodied energy consumption and aligning themselves with typical client interests (i.e. operational energy phase). The contractor can highlight the energy and associated cost savings that can be achieved through better predictions and understanding of initial energy use during the construction phase of specific project types. During the pre-construction phase, the contractor can now provide evidence highlighting the importance of data capture and management to potential sub-contractors; reflecting required standards for data content, detail and terminology. Also the contractor can begin to create initial embodied energy benchmarks and incentives for specific construction activities, packages and sub-contractors to improve the scope of their environmental management system. During the on-site construction phase, the contractor can now capture detailed initial embodied energy data to formulate project specific datasets which can be integrated back into the wider organisation and support future projects during tender and pre-construction phases.

6.3 Implications for the Industry

The complexity of construction projects, the deficiency of available data, the lack of standardised methods for data capture, and data assumptions made by practitioners are all issues previously highlighted in industry literature that have previously limited the awareness and application of initial embodied energy consumption (Treloar et al., 2000; Scheuer et al. 2003; Sodagar and Fieldson, 2008; Optis and Wild, 2010; Dixit et al. 2012). This research project has attempted to alleviate these issues and provide a useful contribution to knowledge by highlighting the important role the contractor can fulfil in terms of capturing, assessing and potentially reducing initial embodied energy consumption within construction projects. The research provides a practical example of how the subject can move forward through exploitation of the contractor's resources, involvement within project procurement and delivery, and overall opportunity to access to initial embodied energy data.

6.4 Contribution to Existing Knowledge and Practice

The research has made the following contributions to existing knowledge and practice surrounding the subject of initial embodied energy consumption within the UK construction industry:

- an insight into the usefulness of current practices employed by a contractor, highlighting their potential use to support an assessment of initial embodied energy, and how these practices are perceived and managed by operatives;
- the development and exploration of a practical approach towards initial embodied energy assessment, demonstrating clear system boundaries, calculation methods and data sources used to evaluate energy consumption across individual life cycle phases which can be redefined within future research;
- an account of practical challenges and opportunities facing a contractor to address initial embodied energy consumption within UK non-domestic construction projects; and,
- an example of how an action research methodology, based upon a mixed methods research strategy, can be used to evaluate live construction project data and develop specified learning within a contractor to reduce initial embodied energy consumption and support future research.

6.5 Critical Evaluation of the Research

Difficulties were presented during attempts to realise the aim and objectives of the research project. In particular the task was hindered due to a lack of UK specific project life cycle data within industry literature, the requirements and time constraints of the research project, changes to the industrial sponsor's company strategy and structure, and the overall working environment within live construction projects.

The research project focused specifically on the operations of one particular large principal contractor based in the UK. Evidently, the contractor only represented a fraction of the capabilities and scope of the UK construction industry in terms of project stakeholders, project portfolio, and knowledge. Hence findings cannot be truly generalised throughout the entire construction industry. Despite potential benefits that could have occurred from exploring the workings of different project stakeholders (e.g. increased awareness of practical challenges, enhanced project datasets, improved generalisation of findings), due to the context of the EngD and intentions of the industrial sponsor to maintain a potential competitive advantage, this additional source of data was not investigated. Nonetheless, to help overcome gaps in industry knowledge and data within industry literature, the research project highlighted a unique, detailed perspective of the workings of a profound stakeholder typically overlooked within previous studies despite their involvement within project procurement and delivery.

Primary data was captured and assessed from three explored live construction projects. The selection of construction projects, construction packages and associated data sources (e.g. current practices, operatives) were influenced due to RE's active involvement within the contractor. Notably, these projects, packages and data sources reflected a small proportion of the contractor's overall project portfolio, scope and resources available throughout the UK construction industry. Though, consideration was given towards the selection of projects, packages and data sources deemed potentially applicable to other contractors due to containing general and common features (e.g. typical multi-storey commercial office project with bespoke design features). The narrow selection of construction projects, packages and data sources helped demonstrate consistency throughout the adopted research cycles which lead to the discovery of certain data which is typically overlooked within previous studies (e.g. embodied energy derived from site area).

Uncertainty within the measured values derived from the explored construction projects was recognised. Evidently the presence of uncertainty influenced the overall reliability and validity of the results, especially as data assumptions were required when data captured was discovered as incomplete. Therefore the overall initial embodied energy findings from each explored construction project would reflect an under of overestimation of the true value. Although, the defined uncertainty and consideration of the key parameters (i.e. system boundaries, calculation methods and data sources) throughout the research project helped increase the overall transparency of the findings which would help focus future research to target improved ways to capture and assess data in order to tackle uncertainties.

An action research methodological approach was undertaken despite previous studies highlighted concerns regarding the method in terms of lack of consistency and closure on particular issues. Notwithstanding the concerns, the method was adopted as it suited the requirements of the EngD and the needs of the industrial sponsor through demonstrating a practical application of knowledge. The supporting mixed methods research strategy enabled complimentary research approaches (i.e. case studies) and techniques (i.e. observational) to be used commonly through the research project to alleviate concerns regarding consistency and demonstrate progressive practical outcomes, in the form of closure, which could be integrated back into the contractor.

6.6 Recommendations for Industry

From the research, a series of recommendations are presented for consideration by contractors and the wider industry to address the challenges and add value to the opportunities supporting reduced initial embodied energy consumption within the UK non-domestic sector:

- Contractors could develop new fiscal incentives for sub-contractors to consider low embodied energy materials and reduced waste consumption before and during on-site construction. This will help identify opportunities to reduce energy and waste consumption throughout different individual life cycle phases. This will also help highlight how, what and when certain solutions should be adopted to provide the most significant energy reduction across all project life cycle phases to aid future construction projects.
- Contractors could develop enhanced guidance documents and minimum standards to assist the capture of initial embodied energy data from different project stakeholders (e.g. designers, sub-contractors, suppliers) based upon current practices. This will help improve the consistency and organisation of captured data and influence the overall stability of results used to aid decision making within future construction projects. This will also help develop datasets from different project types and locations to stimulate future best practice and lessons learned.
- Contractors could encourage increased data transparency across project stakeholders and develop improved data authentication techniques in line with current practices. This will help improve the overall appropriateness and usefulness of results intended to aid decision making within future construction projects across different sectors. This will also help improve knowledge share throughout and realisation of how to

tackle total project life cycle energy at different project life cycle phases with respect to the individual intentions and responsibilities of different project stakeholders.

- Contractors could develop and share project case study data reflecting detailed primary data from different construction projects. This will help formulate benchmarks and targets to drive reduced energy consumption reductions across specific construction packages, activities and sub-contractors with regards to individual life cycle phases. This will also help improve knowledge of the impact project procurement and delivery has on project life cycle for various project stakeholders.
- Clients could improve awareness and application of a life cycle approach within project scope and tenders through new fiscal incentives and requirements for project stakeholders to use BIM. This will encourage project stakeholders to invest in improved internal knowledge and resources designed to accommodate a life cycle approach towards project design, procurement and delivery, intended to make these stakeholders more marketable. This approach can also help further validate the usefulness of the practical framework with regards to the requirements of BIM.
- The UK construction industry could encourage project stakeholders to capture detailed data from various project life cycle phases and contribute towards the open publication of data. In turn this will help stimulate a foundation of freely available data used by practitioners within industry and academia to support further research and development. Also the industry could produce best practice examples and training to identify practical ways to address project life cycle energy and provide associated benefits to project stakeholders. This will help further improve skill and competency

of the UK construction workforce, including contractor operatives, leading to a potential generation of new ideas and solutions.

6.7 Future Research

From the research, the following recommendations are presented for consideration within future studies. This research:

- Identified some merit towards developing modelled equations from the regression analysis to predict future construction phase energy consumption. Evidently, there is a need to improve these models to consider the influence of additional project variables and life cycle phases across different project types, required to support the formation of targets.
- Highlighted the relative significance of individual project life cycle phases with regards to construction packages within a small sample of UK non-domestic construction projects. There is a need to investigate this relative significance and construction packages within a larger sample of different project types across varied sectors to establish possible trends in energy consumption to develop a series of ‘quick wins’ to potentially reduce consumption.
- Developed a framework to assess initial embodied energy performance derived from current practices and views from one UK contractor. There is a need to distinguish the use of the framework and generalisation of findings by exploring the workings of other contractors which vary in size and operation.
- Confirmed the importance of material phase energy in comparison to transportation and construction phase energy within the specific sample of explored construction projects. There is a need to understand the relationship between and changes to initial

embodied energy phase consumption which result from project procurement and delivery alterations, to better inform the decision making process.

- Highlighted the importance of acknowledging total project life cycle energy and building lifespan during the project decision making process. Evidently there is a need to recognise the impact decisions made during project development, towards reducing operational energy, have on initial embodied energy consumption across different project types. There is a need to understand the most effective approach towards tackling total project life cycle energy as decisions made during different project stages could result in different consequences in terms of reduced energy and experienced risk and reward by project stakeholders.
- Acknowledged difficulties with regards to capturing and assessing large quantities of data from contractor current practices. There is a need to explore the potential for automated data capturing mechanisms to be used to improve the validity and accuracy of data captured from project resources across various initial embodied energy phases.
- Recognised contemporary developments within literature regarding the application of initial embodied energy performance. Firstly, there is a need to examine the use of BIM to incorporate initial embodied energy datasets intended to support live project decision making and benchmarking of project life cycle energy. Secondly, there is a need to comprehend how life cycle impacts of construction materials and projects will be evaluated according to the CEN TC 350 standards, to better align current practices and data capture.

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APPENDIX A ON-SITE ENERGY MANAGEMENT (PAPER 1)

Full Reference

Davies, P.J., Emmitt, S., Firth, S.K. (2013a) On-site energy management challenges and opportunities: a contractor's perspective. *Building Research & Information*, 41(4), 450-468.

Abstract

The UK government has established numerous directives and policies to encourage CO2 and energy consumption reduction within the non-domestic sector. Current legislative measures are primarily focused towards reducing operational impacts, largely overlooking embodied impacts, in particular within the construction process. On-site construction refers to the energy consumed during the installation of materials up to project practical completion and represents the largest share of construction process CO2 emissions. Contractors have a pivotal role to play in advancing the CO2 and energy consumption reduction agenda owing to their significant involvement in project procurement and on-site construction. Hence, the research aimed to investigate the key challenges and opportunities for delivering on-site energy management within UK non-domestic projects from a contractor's perspective.

The research adopted a case study methodological approach within a UK large principal contractor explored via a desk study, quantitative analysis, and multiple semi-structured interviews investigating on-site energy management amongst a wide geographical sample of non-domestic projects and operatives. The research found shortcomings within the contractor's current on-site energy management procedure across the three reporting levels (Director, Operations, and Project). Findings identified the lack of data authentication as a significant challenge, whereas capturing additional project variables to facilitate future benchmarking was deemed as a key opportunity for on-site energy management enhancement.

Keywords

On-site construction, energy management, contractor, environmental performance indicators, non-domestic.

Paper Type – Journal Paper

Referred Name – Paper 1

1 INTRODUCTION

There is clear evidence that the UK and the rest of the World need to tackle the adverse effects of climate change. The construction industry accounts for 40% of the entire CO2 emissions arising from the developed world (UNSBCI, 2009). Increasing energy efficiency and reducing CO2 levels are key policy objectives for the International Energy Agency (IEA) (Scholtens and Kleinsmann, 2011). The non-domestic sector accounts for approximately 18% of the UK's total CO2 emissions (operational and embodied), thus providing vast opportunities for CO2 and energy consumption reduction (BIS, 2010; Carbon Connect, 2011). Project life cycle energy is derived from operational and embodied energy impacts. Operational energy relates to the energy used during building occupier activity, whereas embodied energy relates to the indirect (energy consumed during extraction and manufacture of raw materials) and direct energy inputs (energy consumed to facilitate transportation and installation of materials) required for construction, renovation, maintenance, refurbishment, modification and demolition (Cole, 1999; BIS, 2010; Dixit et al., 2010; RICS, 2010). In order to achieve zero carbon targets evidence suggests solutions such as super-insulated walls and windows, which contribute to operational energy reduction through high embodied energy materials, is likely to increase in the future. Therefore improving embodied energy efficiency is an effective way to decrease project CO2 emissions and energy consumption levels (Huberman and Pearlmutter, 2008; DECC, 2009a; Kneifel, 2010; RICS, 2010).

The construction process contains direct energy inputs and defined as the "transport, enabling works, assembly, installation and disassembly activities necessary to deliver the service of construction" (Ko, 2010:11). This process consumes a substantial proportion of available natural resource and energy as well as contributes towards environmental pollution (Spence and Mulligan, 1995; Dixit et al., 2010). Previous research has focused towards the quantification and management of building operational energy (Firth et al., 2008; Hinnells, 2008; Tassou et al., 2011) while limited emphasis has been directed towards embodied energy relating to the construction process, namely on-site construction. On-site construction forms one aspect of project direct energy and relates to the energy consumed during the installation of materials up to project practical completion. On-site construction is commonly powered via a mixture of petrol, diesel, gas, and electrical energy usage which ultimately impacts project environmental performance through the release of CO2 emissions during fuel combustion. At present, data typically captured from on-site construction is not detailed enough to set benchmarks and targets for CO2 and energy reduction, in order to increase attention towards energy efficient on-site operations (BIS, 2010). Nonetheless, the contractor is deemed responsible for the consumption and management of this energy and the wider project environmental performance by capturing, verifying and reporting data; as addressed within current forms of environmental measurement such as BREEAM (Shen et al., 2005; ISO 14064-1, 2006; BIS, 2010; DECC, 2010; Dixit et al., 2010; Goggins et al., 2010; RICS, 2010; BRE, 2011; Monahan and Powell, 2011; Tan et al., 2011). Thus in recent years a specific UK large principal contractor has developed a cross-organisational reporting procedure known as the Environmental Performance Indicators (EPI) designed to encapsulate the environmental performance (related to energy, water, waste and timber usage) of their UK construction projects. Hence, this research aims to investigate the key challenges and opportunities for delivering on-site energy management within UK non-domestic projects from a contractor's perspective. The specific objectives of this research are the following: to examine the contractor's current on-site energy management practices; to explore the usefulness of the contractor's historic EPI data for predicting on-site energy consumption; and to evaluate the contractor's perception of on-site energy management in order to add value to the opportunities and address the challenges.

2 ON-SITE ENERGY MANAGEMENT DRIVERS

The EU and the UK government have launched many directives, policies and initiatives intended to drive CO2 and energy consumption reduction within the UK non-domestic sector, namely: the EU Renewable Energy Directive; the Energy Performance of Buildings Directive (EPBD); the Climate Change Act 2008; and the UK Low Carbon Transition Plan (LCTP) (Legislation, 2008; DECC, 2009a; DECC, 2009b; DIAG, 2011). The LCTP plots how the UK will reduce its Greenhouse Gas (GHG) emissions by at least 34% by 2020 relative to the 1990 baseline, though interestingly, it stipulated no reductions are necessary from construction processes in any of the budget periods (2008-12, 2013-17 and 2018-22) (BIS, 2010; SFfC, 2010a).

At present there appears to be modest literature focus towards energy reduction within the construction process, especially on-site construction. Previous studies have shown on-site construction can represent up to 7% of project life cycle energy, depending upon building type and lifespan (Adalberth, 1997; Cole, 1999; Lane, 2007; Smith, 2008). However, studies appear assorted in terms of definitions, data collection techniques and boundaries. Consequently, it seems little is understood within the industry regarding the true significance of on-site construction and its influence across different aspects of project life cycle energy (i.e. material, transportation, operational related energy). Nonetheless, due to anticipated future energy price rises UK contractors appreciate the need to reduce energy demand and develop energy efficient on-site operations. Ko (2010) recently reported the use of energy efficient site accommodation, construction plant and reduced reliance on red diesel power generators can lead to an annual carbon savings (and fuel cost savings) of 200,000 tonnes (£45 million), 84,000 tonnes (£19 million), and 45,000 tonnes of CO2 (£7 million) respectively. Furthermore, the introduction of the Carbon Reduction Commitment (CRC) Energy Efficient Scheme has provided a mechanism for change (DECC, 2010; Carbon Connect, 2011). The CRC, compulsory for organisations (including contractors) consuming more than 6,000 MWh of half-hourly metered electricity, intends to reduce GHG emissions that are not encapsulated by the Climate Change Agreement (CCA) and EU Emissions Trading Scheme (ETS), and aims to improve energy efficiency through carbon taxation and increased environmental performance transparency (DECC, 2010; SFfC, 2010a; Carbon Connect, 2011). In addition to electrical data, organisations are required to report on a wide range of fuel usage such as petrol, diesel, and gas (Energy Team, 2010; Legislation, 2010). Moreover, the voluntary reporting initiative Carbon Disclosure Project (CDP) along with industry guidance developed by Defra/DECC are encouraging organisations to measure and publicise their direct, in-direct and supply chain related environmental impacts (CDP, 2009; IEMA, 2010; Carbon Connect, 2011). The evidence suggests current industry drivers can provide opportunities for organisations, such as contractors, to improve reporting procedures and help industry benchmark on-site energy consumption performance (BIS, 2010; Ko, 2010).

3 THE UK NON-DOMESTIC SECTOR

The UK non-domestic sector contains approximately 1.8 million buildings across an array of project types accounting for 18% of the UK's total CO2 emissions (operational and embodied). Industrial (23%) and retail projects (18%) consume the largest proportion of total UK non-domestic CO2 emissions, whereas other typical project types such as education (including schools, colleges and universities) and healthcare (including GP surgeries, hospitals, and health centre and clinics) are responsible for 11% and 1% respectively (BIS, 2010; Carbon Connect, 2011; BRE, 2012). CO2 emissions from this sector have been almost static since 1990 because emission reductions have been counteracted by increased building floor areas (Ravetz, 2008; Carbon Connect, 2011). Nonetheless, reducing CO2 emissions from the sector by 35% by 2020 could result in a financial cost saving of more than £4.5 billion for the UK economy (BIS, 2010).

Evidence suggests the UK construction industry can potentially influence 47% of total UK CO2 emissions, with all building operation and on-site construction representing 83% and 1% of the total respectively (BIS, 2010). Nonetheless, during 2008 the contractors output (i.e. the amount of construction activity undertaken per annum) across the UK (not including Northern Ireland) was £123.58 billion, whereby new education and healthcare projects represented 13% and 7% respectively (SFfC, 2010a; ONS, 2011; BRE, 2012). During the same year, the construction process produced 5.87 MtCO2 derived from the following approximate contributions: on-site construction 34% (2.01 MtCO2); freight transport 32% (1.86 MtCO2); business travel 15% (0.86 MtCO2); waste removal 10% (0.6 MtCO2); off-site offices 5% (0.27 MtCO2); and off-site assembly 5% (0.27 MtCO2) (Ko, 2010; SFfC, 2010b). In particular, in terms of on-site construction emissions, new non-domestic represented 28% (0.56 MtCO2) and specifically new education and healthcare projects signified 4% (0.08 MtCO2) and 3% (0.05 MtCO2) of the total respectively (SFfC, 2010b). Thus applying the current CRC carbon tax of £12/ tCO2 to the previous 2008 on-site construction emissions figure for new non-domestic sector projects (0.56 MtCO2) could have potentially resulted in a financial burden of approximately £6.72 million shared amongst all responsible organisations (SFfC, 2010a; Environmental Agency, 2012). Specifically new education and healthcare projects could have potentially been responsible for £0.96 million and £0.6 million of the financial burden respectively. Overall, despite on-site construction appearing relatively insignificant in comparison to operational energy, there is evidence to suggest on-site construction is important from a contractor's perspective considering the overall annual volume of construction work available within the industry and the current associated financial burdens.

4 ON-SITE ENERGY MANAGEMENT CURRENT PRACTICE

It seems there is a clear resurgence in energy consumption research notably since the rise of Life Cycle Assessment (LCA) during the early 1990s and attempts for its standardisation (BSRIA, 2011). Subsequent research studies have explored a raft of interrelated energy terms (operational, embodied, direct, indirect, primary and end-use) though most have focused on individual phases rather than whole life cycle energy (Gustavsson et al., 2010). Despite this, energy consumption derived from on-site construction activity is commonly ignored in studies owing to the lack of available data and the inconsistent use of LCA boundaries; encouraging researchers to dispute its significance compared to whole life cycle energy (Fay et al., 2010; Cole, 1999; Ding, 2004; Smith, 2008; Dixit et al., 2010; Gustavsson et al., 2010).

4.1 ENERGY PHASES

In order to reduce widespread industry energy use BIS (2010) acknowledged the need to diminish both project life cycle energy phases; operational and embodied. It was previously identified operational energy relates to energy used during building occupier activity, whereas embodied energy relates to the indirect and direct energy inputs required for various forms of construction (Cole, 1999; BIS, 2010; Dixit et al., 2010; RICS, 2010). On-site construction forms a proportion of embodied energy relating to the energy consumed during the installation of materials up to project practical completion. In general, evidence suggests both energy phases are noteworthy contributors towards building life cycle energy demand, typically operational 80-90% and embodied 10-20%; thus understanding the relationship between the two is critical to reduce overall project energy consumption (Lane, 2007; Ramesh et al., 2010; Van Ooteghem and Xu, 2012). RICS (2010) suggested reducing embodied energy through design is more economical than reducing operational emissions. Nevertheless, Monahan and Powell (2011) observed that in practice embodied energy is not considered when a building is being designed, specified and constructed.

In contrast, Gustavsson et al. (2010) argued operational energy reduction should be considered before embodied energy as it represents the largest share in life cycle energy and increases as building lifespan prolongs. However, due to advances in energy efficient materials, equipment and appliances, the potential to reduce operational energy has increased (Nassen et al., 2007; Sartori and Hestnes, 2007; Dixit et al., 2010). Although conversely, it seems operational energy use is increasing due to higher demand for electrical equipment and appliances (Hinnells, 2008; Menezes et al., 2012). Nonetheless, the intention to reduce operational energy levels within the UK non-domestic sector remains clear. Current UK government targets, Part L of the Building Regulations and forms of environmental measurement (i.e. BREEAM, EPCs, DECs) are all driven towards reducing operational energy; overlooking embodied energy. Consequently, achieving these requirements could inexorably increase embodied energy levels; the process would be counterproductive, though legislatively correct (DECC, 2009a; BIS, 2010; RICS, 2010).

4.2 ON-SITE MONITORING

The creation of the CRC has encouraged contractors to quantify and potentially benchmark a proportion of project building embodied energy through the collection and assessment of their on-site energy consumption; namely via petrol, diesel, gas, and electrical energy usage. Though, due to project nature, complexity and timescale this quantification is a complex, non-uniform and time consuming process (Miller, 2001; Langston and Langston, 2008; DECC, 2010; Ko, 2010; Carbon Connect, 2011). In general, existing embodied energy inventories and methodologies (Buchanan and Honey, 1994; Alcorn and Baird, 1996; BSRIA, 2011) are designed to help practitioners quantify and hence understand the multiple forms and significance of embodied energy (i.e. material, transportation, operational related energy). Although, Dixit et al. (2010) suggested at present these are insufficient and inaccurate due to parameter variation relating to the diverse stages of an embodied energy LCA. Also, current inventories suffer from problems of disparity and incomparability with no standard protocols for embodied energy computation. Hence, these views are supported by the varying success previously experienced by researchers whilst investigating embodied and operational life cycle energy phases through on-site monitoring practices. Monahan and Powell (2011) for instance investigated energy consumption during on-site construction via energy meter readings and fuel receipts, though this study was unsuccessful in disaggregating energy consumption per building activity and package as only total on-site energy as an aggregated figure was achieved. However in contrast, Gill et al. (2011) investigated the energy performance of 25 occupied domestic buildings and were able to compare performance against national averages, low energy benchmarks and UK regulations via the collection of on-site electrical, heat and water consumption data across a range of monitoring intervals.

5 METHOD

The research implemented a case study methodological approach within a large principal contractor based in the UK, consisting of a desk study, quantitative analysis, and multiple in-depth semi-structured interviews. This approach was adopted to create a detailed view of the subject intended to increase the validity of the findings (Fellows and Liu, 2008). The contractor provided a suitable sample as literature identified they have: an essential role during the construction phase; a responsibility towards promotion of sustainable development; and a commitment towards reducing negative impact on both environment and society (Shen and Zhang, 2002; Shen et al., 2005; Tan et al., 2011).

The desk study provided both an internal contractor and industry-wide perspective of on-site energy management. The quantitative analysis explored the usefulness of historic Environmental Performance Indicators (EPI) data towards predicting on-site energy consumption. The contractor started 30 non-domestic sector construction projects throughout England between January 2010 and December 2011 of these 24 new-build projects (80%) were fully completed through the duration of the research and provided comprehensive, comparable data that could be explored and therefore included in the analysis. Consequently, outcomes were discussed through multiple semi-structured interviews identifying similarities and differences between the contractor and industry knowledge. Overall, 10 non-domestic sector operatives were selected at random across each of the three EPI procedure reporting levels (Director, Operations, and Project) whereby 17 operatives (57%) agreed to participate within the interviews.

Quantitative analysis explored the usefulness of historic EPI data for predicting on-site energy consumption performance. The Statistical Package for Social Science (SPSS) 19.0 software was used to evaluate the sampled data (Field, 2009). A series of multiple linear regression models were created using backward selection methods to distinguish potential connections between different project types, project variables and dependent variables. Project variables and associated interaction terms with two-tailed significant values of less than 10% were maintained within the model and included in the resultant modelled equations intended to predict on-site energy consumption performance. Regression diagnostics were used to determine the assumptions and accuracy of the modelled data; also log transformations were used to reduce the subsequent prediction errors (Field, 2009).

Multiple face-to-face semi-structured interviews were used to build upon the evidence derived from the desk study and quantitative analysis, extracting information from a range of operatives across the three EPI procedure reporting levels. The 45 minute long interviews enabled participants to elaborate on their responsibility, understanding and interaction with the EPI procedure; and, stimulated an interviewer-interviewee interactive discussion on the subject. The qualitative interviews were recorded to generate full transcripts which were then classified into key themes, before being analysed via the use of a matrix table (Bryman, 2004).

6 RESULTS AND DISCUSSION

The results obtained from the desk study, quantitative analysis and interviews provided insights into on-site energy management current practice, challenges and opportunities from a contractor's perspective. Overall, the quantitative analysis explored the historic EPI data captured from 24 non-domestic construction projects and the face-to-face interviews captured the opinions from 17 non-domestic operatives. Due to variation within the geographical location of available construction projects and operative numbers across the EPI procedure reporting levels (Director, Operations, and Project), the results were exclusively captured from operatives and projects within England. Table 1 underlines the varied occupational backgrounds presented by the interviewees across the three reporting levels.

Table 1 Geographical distribution and occupations of the contractor's interview participants

Ref.	Location[a]	Reporting Level[b c d]	Occupation	Gender	Age Group[e]	Experience[f]
1	North West	Project Level	Contracts Manager	Male	45-49 Years	21 Years
2	North West	Project Level	Senior Engineer	Male	30-34 Years	11 Years
3	North West	Project Level	Assistant Engineer	Male	20-24 Years	4 Years
4	North West	Project Level	Senior Engineer	Male	30-34 Years	14 Years
5	South West	Project Level	Administration	Female	20-24 Years	3 Years
6	North East	Operations Level	Design Coordinator	Male	20-24 Years	3 Years
7	Midlands	Operations Level	E&S Consultant	Male	25-29 Years	5 Years
8	Midlands	Operations Level	Administration	Female	40-44 Years	7 Years
9	Midlands	Operations Level	Estimator	Male	30-34 Years	15 Years
10	Midlands	Operations Level	Commercial Manager	Male	30-34 Years	14 Years
11	South East	Operations Level	Design Coordinator	Male	25-29 Years	4 Years
12	North East	Director Level	Director	Male	40-44 Years	21 Years
13	Midlands	Director Level	Director	Male	40-44 Years	21 Years
14	Midlands	Director Level	Director	Male	45-49 Years	23 Years
15	Midlands	Director Level	Regional Director	Male	50+ Years	25 Years
16	Midlands	Director Level	Production Director	Male	45-49 Years	24 Years
17	South East	Director Level	Managing Director	Male	50+ Years	32 Years

[a] Location; geographical location within England.
[b] Director Level operatives; responsible for corporate management and strategy.
[c] Operations Level operatives; responsible for tender management and support services.
[d] Project Level operatives; responsible for on-site operations during construction.
[e] Age Group; 20-24; 25-29; 30-34; 35-39; 40-44; 45-49; 50+ Years.
[f] Experience; total number of years industry experience.

6.1 DESK STUDY

During 2010 the contractor developed a cross-organisational reporting procedure known as the Environmental Performance Indicators (EPI) designed to encapsulate the environmental performance (related to energy, water, waste and timber usage) of all UK construction projects in accordance with reporting requirements addressed by the contractor's parent organisation and CRC (DECC, 2010). The EPI reporting procedure is managed by the contractor's Environmental and Sustainability (E&S) Team, requiring action from Divisional Directors, Regional Representatives (Regional Directors, Operational Managers or Personal Assistants) and project specific Nominated Responsible Individuals (NRI's).

Once a contract is awarded the E&S Team produce a generic online Excel Workbook containing a Reporting Sheet requiring project environmental performance data input. The specific energy consumption data is derived from primary evidence such as utility bills, meter readings and fuel delivery notes relating to contractor, sub-contractor and client petrol, diesel, gas, and electrical energy usage; as expressed by the CRC requirements (DECC, 2010). The project specific NRI is responsible for the continual completion of the Reporting Sheet one month in arrears; providing a month to capture, verify and report the necessary data, as illustrated in Figure 1. The NRI is expected to complete their Reporting Sheet requirements by the first Monday of each month with the contents being reviewed and authorised by the Project Manager. Once completed, the data is validated by Divisional Directors and Regional

Representatives whereby anonymous or inconsistent data is reported back and changed by the NRI. This is a continuous process of validation until the following Friday whereby the data is formally submitted to the E&S Team. Once submitted, the E&S Team critically review and compare all data against values outlined within the contractors commercial web based database; Construction Industry Solutions (COINS) (COINS, 2011). The database details the contractor's financial expenditure due to energy use for each project. Differences between COINS values and captured data are highlighted and communicated back to the corresponding Divisional Directors and Regional Representatives for further improvement. Equally, this is a continuous process until the 14th day (final reporting deadline) of each month.

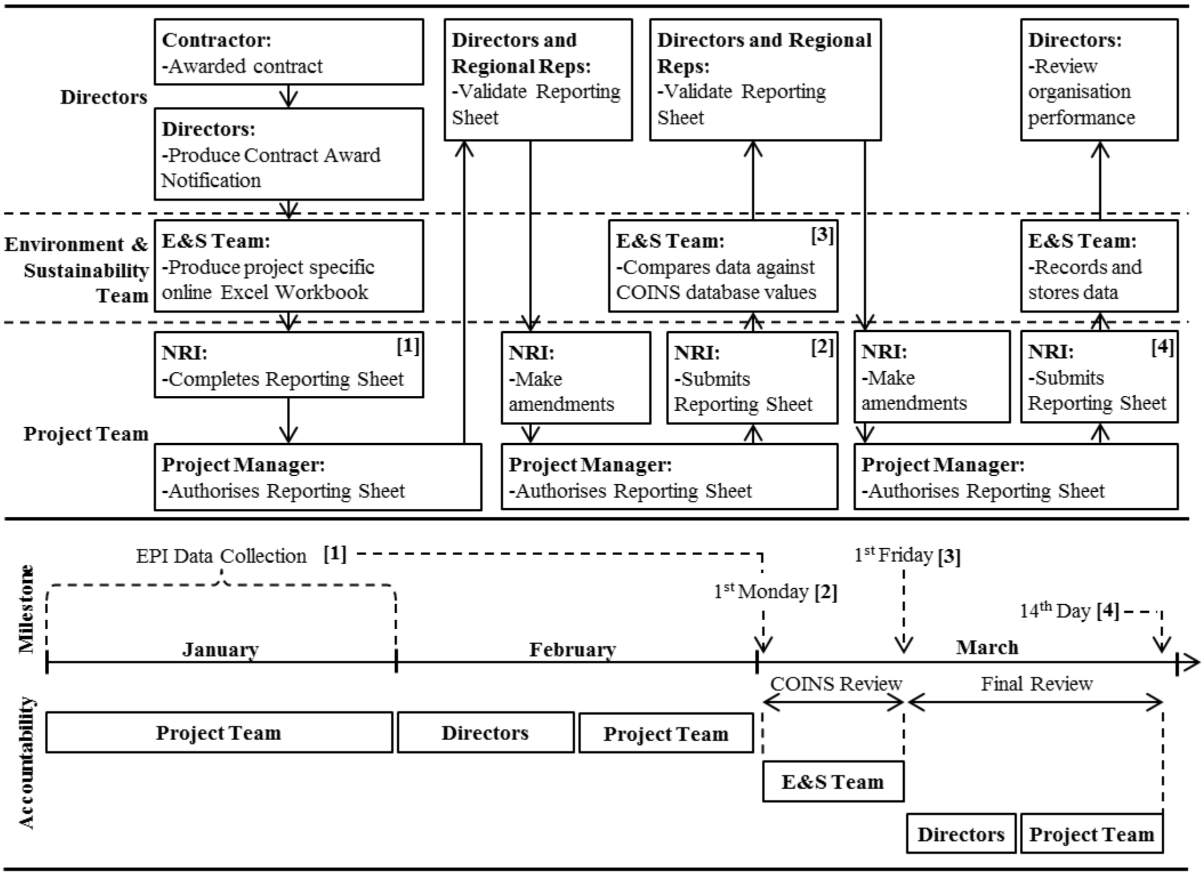

Figure 1 The transfer of information within the contractor's Environmental Performance Indicator (EPI) procedure

6.2 QUANTITATIVE ANALYSIS

The quantitative analysis explored the usefulness of historic EPI data for predicting on-site energy consumption (i.e. electrical and red diesel usage). The analysis was based upon the type and level of project information and captured by the contractor in order to support their internal reporting and CRC requirements. Overall 24 new-build projects which were fully completed between January 2010 and December 2011 throughout England were included within the analysis. The sample was derived from a mixture of education and healthcare projects, such as: colleges, schools, universities and hospitals. These projects represented typical education and healthcare projects with no bespoke design features, functional facilities or high performance environmental measurement requirements (i.e. via BREEAM). Table 2 displays the captured project variables and electrical and red diesel consumption levels across the selected projects.

Table 2 Captured project variables and on-site energy consumption levels from the contractor's EPI procedure (Jan 2010 and Dec 2011)

Project Number[a]	Project Type	Loc[b]	Duration	Turnover[c]	Site Area[c]	DS[c]	IS[c]	Electricity[c]	Red Diesel[c]
Project 1	College	SE	10 months	7,200,000	12,000	103	810	274,419	0
Project 2	College	SE	12 months	1,600,000	506	12	176	2,515	0
Project 3	College	SE	15 months	18,600,000	43,750	149	1463	47,784	11,656
Project 4	Hospital	SW	9 months	15,600,000	10,131	79	370	9,710	23,587
Project 5	Hospital	SW	15 months	3,200,000	1,500	49	255	134,976	200
Project 6	Hospital	SE	14 months	1,700,000	432	50	239	39,903	3,592
Project 7	Hospital	NW	18 months	14,200,000	30,000	201	955	205,424	11,462
Project 8	Hospital	NW	16 months	20,900,000	10,000	206	2205	60,000	8,500
Project 9	School	NW	13 months	9,300,000	124,000	90	750	32,909	0
Project 10	School	NW	19 months	20,400,000	12,813	205	1704	39,365	15,249
Project 11	School	SW	10 months	2,000,000	20,920	30	310	58,822	986
Project 12	School	NW	16 months	13,800,000	37,500	232	1568	90,287	82,426
Project 13	School	NW	21 months	22,100,000	29,635	260	1083	263,915	70,631
Project 14	School	NW	15 months	11,400,000	21,165	158	108	189,636	9,224
Project 15	School	SW	7 months	1,100,000	1,400	10	194	559	15
Project 16	School	SE	11 months	2,900,000	1,728	43	316	48,209	205
Project 17	School	Mid	11 months	3,400,000	16,876	46	350	0	28,457
Project 18	School	SW	12 months	10,600,000	42,386	87	725	66,372	35,823
Project 19	School	Mid	15 months	4,800,000	2,744	63	437	72,136	10,500
Project 20	School	SW	12 months	7,300,000	40,000	26	39	94,241	2,951
Project 21	School	Mid	14 months	5,600,000	3,313	76	405	118,497	10,973
Project 22	University	Mid	15 months	17,800,000	14,500	151	1105	794	83,811
Project 23	University	SE	21 months	54,000,000	15,050	384	2746	409,834	20,194
Project 24	University	Mid	18 months	19,000,000	17,406	264	1823	175,436	96,238

[a] Note, all projects are new-build.
[b] Loc; geographical location within England.
[c] Project variables; Turnover (£); Site Area (m^2); DS, Direct Staff (No.); IS, Indirect Staff (No.); Electricity (kWh); Red Diesel (litres).

6.2.1 MODEL DEVELOPMENT

A series of multiple linear regression models were developed throughout a two stage approach. These models were created using backward selection methods to distinguish the importance of each project variable (i.e. turnover, site area, direct staff and indirect staff) towards predicting the performance of the dependent variables (i.e. on-site electrical and red diesel consumption) across all and specific project types. The models derived from 339 monthly historic EPI data entries consisting of 339 turnover, site area, direct staff, indirect staff values; and 288 electrical energy and 156 red diesel consumption values. In particular, the term 'turnover' relates to project value and is used by the contractor to normalise all captured project data throughout the organisation. It is envisioned that as direct staff and indirect staff levels increase this will drive an increase in energy consumption which will be reflected within an increase in turnover.

During the initial stage, two models were developed for each dependent variable based upon all and specific project type data. These models established assorted project variables as significant for different project types. Thus, in order to investigate the relationship between project types, project variables and dependent variables across the sample, an overall model combining all data (including multiple interaction terms) was developed for each dependent variable. This overall model was created to determine whether it could successfully fit the sampled data and potentially generalise to other samples. Although, the corresponding regression diagnostics revealed non-linearity and non-constant variance across the modelled data, hence log transformations were used to reduce the subsequent prediction errors. Therefore, during the final stage two new models were developed; one model considered the influence of project type as opposed to the other. Each new model consisted of a different set of modelled equations intended to predict the performance (i.e. natural logarithmic values) of each dependent variable. Table 3 displays the composition of the modelled equations for electrical and red diesel consumption prediction derived from the two models; ‘All Projects’ (AP) and ‘Project Type’ (PT) specific. It seems assorted project variables and interaction terms are significant for different project types. All project variables captured by the EPI reporting procedure are in some degree included within the modelled equations. Also, it appears turnover upholds a varied impact on the rate of increase in electrical energy consumption across all forms of modelled equations. The influence of site area on red diesel consumption within college and university projects is factor of 10 greater than for school or hospital projects. Additionally, direct staff maintains a positive influence on both electrical and red diesel consumption across all forms of modelled equations. Interestingly, indirect staff was not included within any AP modelled equations whereas it was the only project variable specified across all PT modelled equations.

Table 3 All modelled equations for electrical and red diesel consumption prediction

Equation Type[a]	Electricity Modelled Equation (kWh)[b]	Red Diesel Modelled Equation (litres)[b]
(AP) All Projects[c]	= [7.202] + [-2.006E-7(T)] + [0.123(DS)]	= [6.364] + [1.591E-5(SA)] + [0.079(DS)]
(PT) College[d]	= [5.112] + [-1.725E-6(T)] + [0.441(DS)] + [7.894E-3(IS)]	= [2.515] + [1.183E-4(SA)] + [0.004(IS)]
(PT) Hospital[d]	= [7.939] + [1.925E-7(T)] + [0.106(DS)] + [-0.006(IS)]	= [7.150] + [-1.922E-5(SA)] + [0.004(IS)]
(PT) School[d]	= [7.331] + [3.613E-7(T)] + [0.136(DS)] + [-0.010(IS)]	= [6.158] + [4.097E-5(SA)] + [0.004(IS)]
(PT) University[d]	= [2.034] + [-1.773E-8(T)] + [0.308(DS)] + [0.008(IS)]	= [6.194] + [1.184E-4(SA)] + [0.004(IS)]

[a] Equation Type; All Projects (AP); Project Type (PT) specific.
[b] Project variables; T, Turnover (£); SA, Site Area (m^2); DS, Direct Staff (No.); IS, Indirect Staff (No.).

[c] Electricity R^2 = 0.138 (Adjusted R^2 = 0.132); Red Diesel R^2 = 0.148 (Adjusted R^2 = 0.136).
[d] Electricity R^2 = 0.385 (Adjusted R^2 = 0.351); Red Diesel R^2 = 0.310 (Adjusted R^2 = 0.277).

6.2.2 MODEL ASSESSMENT

Overall, both models experienced varied success towards predicting the performance of the dependent variables. Table 4 demonstrates a comparison between the ability of each model to predict the performance of each dependent variable based upon the corresponding AP and PT modelled equations. In particular, the table highlights the actual sampled data and the modelled data derived from the corresponding regression analysis. The difference between these two figures is the standardised residual value which represents the level of error (as a %) within the modelled equations.

In terms of predicting electrical energy consumption, the AP modelled equation demonstrated wide fluctuations results with no clear connection between assorted project variables. Likewise, even though the PT modelled equations reflected very accurate predictions for two school projects in particular (Project 13 and 19), all project variables between these projects including total electrical energy consumption were significantly different. Moreover, despite different approaches, both AP and PT modelled equations experienced major difficulty in predicting the performance of Project 15 and 22. Interestingly, both projects contained the smallest electrical energy consumption throughout the sampled data, thus the evidence seems to suggest both approaches are inaccurate at predicting very small consumption performance. In contrast, considering the largest consuming project (Project 23), the AP modelled equation did outperform the PT modelled equation. However, this appears to be an anomaly as this was the only occasion throughout the top 10 consuming projects whereby the AP modelled equation was more accurate.

In terms of red diesel consumption, similar to electrical energy consumption, the evidence suggests both approaches are unsuccessful at predicting small consumption performance. In addition, both AP and PT modelled equations experienced significant difficulty in predicting consumption performance for Project 15. This project included only 7 monthly data entries for each project variable; reducing the ability of the modelled equation to accurately reflect the sampled data. However for Projects 5 and 16, these projects contained 15 and 11 monthly data entries respectively, and still concluded inaccurate modelled results. Considering Project 21, even with the site area being a factor of 10 smaller than for Project 12, both included approximate residual values of 0.4% and 0.2% respectively.

Table 4 Comparing the performance of all modelled equations for electrical and red diesel consumption prediction per project type (natural logarithmic values)

Sampled Data				'All Projects' (AP) Modelled Equations				'Project Type' (PT) specific Modelled Equations			
Project Number	Project Type	Electricity Actual	R' Diesel Actual	Electricity Modelled[a]	Residual (%)	R' Diesel Modelled[a]	Residual (%)	Electricity Modelled[b]	Residual (%)	R' Diesel Modelled[b]	Residual (%)
Project 1	College	94.53	0	83.20	-11.99	0	0	90.40	-4.37	0	0
Project 2	College	63.74	0	87.56	37.37	0	0	65.09	2.12	0	0
Project 3	College	105.63	31.02	107.26	1.54	29.65	-4.42	108.41	2.63	31.03	0.03
Project 4	Hospital	16.92	68.69	15.96	-5.67	64.98	-5.40	17.78	5.08	64.06	-6.74
Project 5	Hospital	125.71	5.30	113.40	-9.79	6.62	24.91	123.41	-1.83	7.18	35.47
Project 6	Hospital	89.29	33.94	84.18	-5.72	32.89	-3.09	90.86	1.76	35.82	5.54
Project 7	Hospital	164.36	87.09	151.45	-7.85	100.64	15.56	161.36	-1.83	88.83	2.00
Project 8	Hospital	102.24	32.02	101.55	-0.67	30.99	-3.22	105.04	2.74	31.18	-2.62
Project 9	School	97.99	0	102.81	4.92	0	0	103.47	5.59	0	0
Project 10	School	130.83	53.03	149.72	14.44	51.98	-1.98	149.08	13.95	49.6	-6.47
Project 11	School	82.30	6.89	75.27	-8.54	6.93	0.58	74.99	-8.88	7.11	3.19
Project 12	School	134.60	105.48	140.92	4.70	106.19	0.67	138.25	2.71	105.3	-0.17
Project 13	School	185.24	83.30	178.69	-3.54	87.66	5.23	186.51	0.69	83.6	0.36
Project 14	School	97.17	65.55	84.24	-13.31	74.84	14.17	90.76	-6.60	70.51	7.57
Project 15	School	30.62	3.91	51.41	67.90	12.94	230.95	51.17	67.11	12.62	222.76
Project 16	School	92.04	5.32	83.92	-8.82	6.87	29.14	84.42	-8.28	6.28	18.05
Project 17	School	0	85.90	0	0	76.60	-10.83	0	0	76.73	-10.68
Project 18	School	55.21	58.89	48.27	-12.57	53.45	-9.24	46.98	-14.91	56.24	-4.50
Project 19	School	117.59	69.07	114.77	-2.40	68.08	-1.43	115.94	-1.40	64.12	-7.17
Project 20	School	104.09	26.27	88.15	-15.31	28.80	9.63	93.76	-9.92	31.27	19.03
Project 21	School	118.63	76.47	108.98	-8.13	82.28	7.60	110.98	-6.45	76.79	0.42
Project 22	University	16.06	111.01	24.85	54.73	95.65	-13.84	19.95	24.22	106.27	-4.27
Project 23	University	190.52	45.94	187.47	-1.60	49.16	7.01	181.60	-4.68	51.79	12.73
Project 24	University	126.88	104.50	158.21	24.69	92.54	-11.44	131.89	3.95	103.4	-1.05

6.2.3 MODEL EFFECTIVENESS

The overall effectiveness of both models varied towards predicting electrical or red diesel consumption performance. The modelled results identified numerous over and under-predictions across all project types. Comparing the total size of error within both AP and PT modelled equations further highlighted the significance of project type within the sampled data.

Generally, the evidence suggests the PT modelled equations were better at predicting on-site energy consumption performance than the AP modelled equations, as illustrated by the overall residual values addressed within Table 5. Although, the AP modelled equations are a useful indicator as they provide relative success whilst using limited information on each project. This helps to reduce the challenges of using a small sample frame per project type. Nonetheless, despite knowing very little about the selected projects there appears to be trends in project variable and on-site energy consumption performance for each unique project type. Each model demonstrated varied prediction performance across various project types. For electrical energy consumption, the PT modelled equations demonstrated accurate consumption predictions for college and hospital projects with the AP modelled equation showing large inaccurate predictions for college and university projects. In terms of red diesel consumption, the PT modelled equations demonstrated similar prediction accuracy for hospital and university projects with the AP modelled equation reflecting large inaccurate predictions. However, the evidence reflected multiple electrical (6%) and red diesel (4%) data outliers within the sampled data used to formulate the two overall multiple regression models. These outliers exceeded the normal distribution assumption parameters for standardised residual values (i.e. values outside +/-1.96) (Field, 2009). The cause of the outliers cannot be truly substantiated from the sampled data alone. However, the probable reason for some remains data entry error; occasionally project variable data differed substantially from the normal trend corresponding to the specific project. For example, sampled electrical energy consumption values per month for Project 13 fluctuated significantly between 13,476 kWh, 12 kWh and 25,045 kWh with respective red diesel values remaining constant. Approximately 45% of all electrical outliers derived from projects initial or last month values and almost half of the total outliers resulted from Project 15. In addition, all red diesel outliers occurred when vast peaks in consumption were experienced without being reflected in associated project variable or electrical energy consumption values.

In summary, it is difficult to draw significant conclusions from the evidence towards predicting on-site energy consumption, due to the overall size of the sample, number of projects per type and numerous unknowns and inconsistencies within the data. Interestingly, these unknowns and inconsistencies within the data seem to question the validity of the overall EPI procedure in order to truly reflect on-site energy consumption performance and whether the data is effectively reviewed before being used to support the contractor's internal reporting and CRC requirements. Nonetheless, both models concluded a separate correlation coefficient value for each dependent variable reflecting the amount of variation in the dependent variable that is accounted for by the model based upon the entire sampled data. The AP modelled equations displayed a correlation coefficient for electrical and red diesel consumption prediction as 0.132 (13.2%) and 0.136 (13.6%) respectively. In contrast, the PT modelled equations demonstrated a correlation coefficient for electrical and red diesel consumption prediction as 0.351 (35.1%) and 0.277 (27.7%) respectively. These outcomes provide some merit towards developing PT modelled equations in order to predict future on-site energy consumption performance, although 64.9% of electrical and 72.3% of red diesel consumption variability is still accounted for by other project variables which are not currently captured within the EPI procedure. Hence at present it is unlikely the contractor could use the data captured within the EPI procedure to formulate potential incentives and targets to drive increased on-site energy efficiency. The type and level of data captured within the EPI procedure does not seem to truly reflect how or why energy is consumed during certain on-site operations and stages during project development. Therefore, to improve the usefulness of the EPI procedure, the contractor could capture additional project variables to increase the granularity of existing data and help generalise the modelled equations to predict consumption performance for projects outside the sample. In general, increasing the sample size could help distinguish a clearer trend in terms of project variables and on-site energy consumption performance per project type and help provide reasoning for (or reduce) errors within captured data.

Table 5 Comparing total residual values of all modelled equations for electrical and red diesel consumption prediction per project type

Sampled Data [a]				AP Modelled Equations [a]		PT Modelled Equations [a]	
Project Numbers	**Project Type**	**Electricity Actual [b]**	**R' Diesel Actual [b]**	**Electricity Residual (%)[c]**	**R' Diesel Residual (%)[c]**	**Electricity Residual (%)[d]**	**R' Diesel Residual (%)[d]**
1-3	College	263.9	31.02	13.94	4.42	3.13	0.03
4-8	Hospital	498.52	227.04	6.41	9.10	2.11	4.83
9-21	School	1246.31	640.08	9.69	7.83	7.90	6.38
22-24	University	333.46	261.45	12.95	11.68	5.34	4.47
	TOTAL[e]	2342.19	1159.59	232.73	102.76	153.01	63.52
	TOTAL (%)[f]	100	100	9.94	8.85	5.76	5.48

[a] Note, all values returned to positive.
[b] Natural logarithmic values.
[c] Electricity Residual (%) = (Total Residual / Total Actual)*100.
[d] Red Diesel Residual (%) = (Total Residual / Total Actual)*100.
[e] TOTAL = Sum of Total Actuals [or] Total Residuals.
[f] TOTAL (%) = (Sum of Total Residuals / Sum of Total Actuals)*100.

6.3 INTERVIEWS

The interviews addressed two fundamental topics amongst Director (DL), Operations (OL) and Project-level (PL) participants: the effectiveness of the EPI procedure towards managing on-site energy consumption data; and in the wider context, how on-site energy management is currently perceived within the contractor. The interviewees were asked to discuss on-site energy management drivers, current practices, challenges and opportunities. The overall findings were derived from 6 Director, 6 Operations and 5 Project-level participants. These are summarised within Appendices 1-3.

6.3.1 ON-SITE ENERGY MANAGEMENT DRIVERS

Participants portrayed vast differences considering knowledge and awareness of on-site energy management drivers currently influencing practices within the contractor and wider industry. DL participants demonstrated a breath of understanding and insight, whereas PL participants portrayed limited perception of current UK policy, legislation and standards. All participants perceived on-site energy consumption as a small fraction of building whole life cycle energy (Smith, 2008), though 80% of PL participants demonstrated no awareness of the need to capture this data for internal and external environmental reporting compliance. In contrast, both DL and OL participants acknowledged parent organisation reporting commitments, the Carbon Reduction Commitment (CRC) Energy Efficiency Scheme, the

Dow Jones Sustainability Index, and the Carbon Disclosure Project as principle on-site energy management drives; views supported by Ko (2010), IEMA (2010) and Carbon Connect (2011). However, it was suggested the contractor is changing behaviour and "willing to adopt more energy efficient practices" to reduce cost; a view strongly supported by Ofgem (2009), DECC (2010) and Morton et al. (2011). Interestingly, fuel consumption was perceived as an "irrelevant factor towards project success" by PL participants, acknowledging no appreciation of how captured data disseminates and influences the actions of the wider organisation. Nevertheless, the DL participants reported that success through on-site energy management practices in general can aid the contractor's Corporate Social Responsibility (CSR) and help to improve value and reputation; views which are consistent with SCTG (2002), Myers (2005) and Jones et al. (2006).

6.3.2 ON-SITE ENERGY MANAGEMENT CURRENT PRACTICE

All participants understood the term operational energy and how it derives from building occupier activities (RICS, 2010). Conversely, the participants portrayed vast dissimilarity in the awareness of embodied energy; despite on-site construction activity contributing towards this energy consumption (Shen et al., 2005; Goggins et al., 2010) and the EPI procedure captures a proportion of this energy phase.

Due to the contractor's commercial success and reputation, a DL participant identified the contractor has been encouraged to "measure and expose our environmental performance", a view supported by Carbon Connect (2011). As the contractor is ISO 14001 accredited, this provided a framework for managing environmental impact (Cascio, 1996; Quazi et al., 2001; IEMA, 2010) and according to a DL participant, improve competitiveness and environmental awareness (Biondi et al, 2000; Nakamura et al., 2001). Nonetheless, an OL participant identified that increased on-site energy management skills are required as current responsibilities for setting targets and identifying opportunities for energy savings are inadequate. It was also suggested these responsibilities are currently shared amongst multiple individuals, instead of a dedicated energy manager as previously sustained by Carbon Connect (2011).

The contractor's communication structure was detailed by a DL participant as a "cascade system" which reflects the internal operating procedure. It was noted that this approach ensures the correct level of commitment and accountability throughout the contractor; a requirement emphasised by Vine (2008). However, the interviewees contradicted this view. The majority of DL participants (80%) demonstrated unfamiliarity with the contractor's current electricity tariff even though one DL participant stated "we have spent a lot of time trying to communicate this tariff". The tariff, which can be used for both new-build and refurbishment projects, provides the contractor with: on-site automated meter readers (electrical, gas and water); an online facility demonstrating the meter reader values; and an improved service agreement enabling an earlier electrical-grid connection. Furthermore, both DL and OL participants emphasised how the original version of the EPI procedure was "not well introduced" and required "vast data processing input from all parties". Although the contractor exhibited willingness to change and build upon their experience by developing "a new harmonised procedure requiring less data processing" actions supported by Peters et al. (2007) and Vine (2008).

6.3.3 ON-SITE ENERGY MANAGEMENT CHALLENGES

The EPI data is not currently used to benchmark project performance. An OL participant explained that this is due to the "overwhelming amount of incorrect, incomplete data received from projects" which make it difficult to quantify, as identified by Jones (2010). Moreover, literature identified that some contractors are encouraging supply chains to adopt energy management practices in order to acquire repeat business (Bansal and Hunter, 2003; Bellesi et al., 2005; Grolleau et al., 2007). However, a PL participant claimed this view is not apparent within the contractor whereby recurrent supply chain members are still "non-proactive and non-insightful into our on-site energy management requirements". All PL participants agreed too much time is spent chasing sub-contractors for the correct information required within the EPI procedure.

In accordance with the literature (Firth et al., 2008; BIS, 2010; Ko, 2010), in-depth sub-metering to capture on-site energy consumption was identified as a positive step towards improving awareness and data accuracy, though this would be "extremely costly and difficult to coordinate". The evidence demonstrated conflicting opinions surrounding the significance of the EPI procedure. In contrast to DL and OL views, the majority of PL participants depict the procedure as a "nuisance rather than a necessity" whereby "the on-site senior management team do not recognise its purpose and benefit". As a result, its responsibility is usually "forced upon a less involved, inexperienced individuals" rather than on-site senior management. All participants portrayed extensive health and safety management consciousness, though PL participants stressed "the same emphasis is not shared for on-site energy management". Given that on-site energy management is a relatively recent requirement this is not an unexpected view.

Most PL participants claimed that they neglected to follow procedure guidance and validate their data before formally submitting to the contractor's Environmental and Sustainability (E&S) Team. Consequently, a PL participant stated that the current procedure included no detailed check for the E&S Team to determine whether monthly information received from projects included data from all active project sub-contractors (which consume energy). This questions the validity of the overall procedure and the ability of the historic EPI data to reflect actual project on-site energy consumption. Additionally, the COINS database was perceived to precisely reflect project financial expenditure in terms of energy consumed though on occasion a discrepancy emerged between COINS and the EPI data; "fuel order values on COINS were greater than delivery note values" as noted by a PL participant. Finding time to capture the required data was portrayed as a significant challenge by the PL participants. This challenge was compounded for refurbishment projects, namely due to the lack of available on-site staff and inconsistency between red diesel generator and electrical mains supply power usage. With refurbishment projects, the contractor's power usage occasionally came from the same electrical mains supply used to power the building, proving difficult to quantify the contractor's actual energy consumption.

6.3.4 ON-SITE ENERGY MANAGEMENT OPPORTUNITIES

A DL participant described the EPI procedure as a clear demonstration of "our organisation's reliance upon accounting towards environmental impact reduction", an idea strongly supported by Gray (2009), Hopwood (2009) and Jones (2010). Although, to improve the effectiveness of the EPI procedure participants identified capturing additional project variables, such as construction package and activity, method of construction, and plant and equipment used could help increase transparency of existing data and improve the understanding of energy consumption during on-site construction. Both DL and OL participants proclaimed this could help formulate the use of future benchmarking, acknowledging the industry need for improved data to assist energy efficient developments (BIS, 2010). Consequently, multiple advantages were identified by the PL participants, such as “increased share of best practice” and “improved competency and competitiveness”. Also, highlighting project performance can be favourable to both “the organisation and client” as agreed upon by Shen and Zhang (2002) and Tan et al. (2011). Furthermore, similar to the CRC’s initial commitment towards public ranking (BIS, 2010), a DL participant confirmed the desire to implement a similar approach to compare project on-site energy consumption performance.

Reliance on red diesel consumption to power initial on-site operations was recognised by all interviewees as contractor current practice (Monahan and Powell, 2011). However, most participants acknowledged an improved reliance towards “an earlier electrical-grid connection to power on-site construction activity instead of using red diesel generators” can ultimately improve accuracy of on-site energy management practices, as portrayed by Ko (2010). Interestingly, a minority of DL and OL participants affirmed this idea has already been recognised namely through the contractor’s “recently established electricity tariff” with one of the UK main electrical suppliers. In essence the tariff “helps to reduce the organisations fuel consumption” by providing improved information and understanding to facilitate energy efficient behaviour; views supported by Firth et al. (2008), Carbon Connect (2011) and Gill et al. (2011). The tariff attempts to remove the challenge surrounding the inability for UK electrical suppliers to plan for a connection due to insufficient construction forecasts from project teams (Ko, 2010). Furthermore, at present the PL participants revealed project teams have “no targets or milestones to complete against” and only receive feedback when “something is wrong”. Therefore, feedback could potentially help project teams improve their approach and awareness as to “why this data is being captured in the first place” a view supported by Stepp et al. (2009).

Overall, the evidence demonstrates vast differences in opinion towards the perception of the EPI procedure across the three reporting levels; mirroring concerns addressed by Lee and Ball (2003). Nonetheless, both DL and OL participants reiterated the significance of on-site energy management understanding and presence throughout the contractor, especially at a senior management level, as previously championed by IEMA (2010) and Carbon Connect (2011).

7 CONCLUSIONS

The research investigated the delivery of on-site energy management from the perspective of a large principal contractor based in the UK. The research highlighted multiple on-site energy management challenges and opportunities present within the contractor’s procurement of UK non-domestic sector projects through investigating the effectiveness of their EPI procedure and associated historic data. Disparity between the three EPI reporting levels (Director, Operations, and Project) was revealed in terms of on-site energy management awareness, commitment and approach.

The quantitative analysis explored the usefulness of historic EPI data for predicting on-site energy consumption through the development of a series of multiple linear regression models. The two models, ‘All Projects’ (AP) and ‘Project Type’ (PT) specific, demonstrated varied success towards on-site energy consumption performance prediction though on average the PT modelled equations were more successful. Although, due to the overall size of the sample, the number of projects per type and the many unknowns and inconsistencies within the data, it is difficult to draw significant conclusions and generalise the results beyond the sample.

During the interviews it was identified that increased on-site energy management skills are required within the contractor, because as current responsibilities for setting targets and identifying opportunities for energy savings are inadequate. The contractor has established a cascade communication structure, which aims to ensure the correct level of commitment and accountability towards on-site energy management. However, the evidence demonstrated vast unfamiliarity across the three reporting levels considering the contractor's current electricity tariff. In accordance with literature, in-depth sub-metering to capture on-site energy consumption performance was identified as a positive step forward although the contractor perceived this as too expensive and difficult to coordinate. Moreover, the findings discovered conflicting opinions surrounding the significance of the EPI procedure with on-site senior management not recognising its purpose and benefit. Evidence suggested that the EPI procedure guidance and authentications were not always thoroughly considered amongst project teams, which questions the validity of the overall procedure and the ability of the historic EPI data to accurately reflect on-site energy consumption performance.

It was previously identified that all on-site construction within the UK represents only 1 % of total UK CO2 emissions and up to 7% of specific project life cycle energy. Despite these figures appearing relatively insignificant in comparison to other life cycle impacts (i.e. operational), it seems from a contractor's perspective that on-site construction impacts are important and require further consideration. The primary function of a contractor is to manage on-site operations and the contractor is deemed responsible for resultant environmental impacts, as identified within BREEAM. However, considering the research findings and current evidence within literature, there appears to be limited knowledge surrounding potential outcomes which could occur from targeting improved on-site energy management. For instance, an increased reliance upon offsite production could lead to higher costs for manufacture and transportation of materials and changes in the contribution of different aspects of project life cycle energy. Reduced reliance on red diesel power generators could lead to increased costs for energy efficient site accommodation and construction plant requirements, as well as potential difficulties surrounding the coordination and delivery of electrical power supply to support on-site operations. Subsequently, this could lead to reduced productivity and poorer quality of workmanship on-site and an increase in overall project duration and cost. Despite the contractor being responsible for on-site operations, different stakeholders (clients, designers etc.) may be better suited to encourage initiatives during on-site construction and also through the wider construction process. It seems the current situation is impeded by the current lack of UK legislative measures which could nurture improvements.

Moreover, the annual volume of construction work, its total contribution towards CO2 emissions and the associated financial burdens (i.e. carbon taxation and continual energy price increases) all seem to further highlight the importance of on-site construction and the need to develop energy efficient on-site operations. This could lead to potential financial and environmental benefits for contractors and the wider industry. Considering the situation from the perspective of the case study contractor is illuminating. During 2010 to 2011 a total of 0.06 MtCO2 was produced from all operations across all sectors, equating to a potential CRC carbon taxation of approximately £720,000. Thus, applying standard conversion factors, it appears that the 24 projects investigated through the quantitative analysis could have contributed to approximately 5% (0.003 MtCO2, £36,000) of the contractor's overall CRC carbon taxation (DECC, 2011). Considering that the 24 projects investigated only represented

10% of the contractor's workload during 2010 to 2011, it seems there are vast opportunities for the contractor (and contractors in general) to reduce their environmental impacts and the associated financial burdens through improved on-site energy management practices.

Despite the multiple views captured through the interviews and the varied success experienced via the quantitative analysis, the overall research findings cannot be easily extrapolated to the wider industry as similar contractors could have different on-site management practices, reporting structures, and policy requirements intended to facilitate on-site operations. Hence, further research is recommended to build upon this investigation by addressing three topics. First, examine views and data from other UK contractors and sub-contractors, which vary in size, in order to compare views on on-site energy management current practices, challenges and opportunities. Second, explore the practicality of delivering in-depth sub-metering to accurately record on-site electrical energy and red diesel consumption. Third, capture additional project variables (i.e. construction package and activity, method of construction, plant and equipment used, site restrictions, client aspirations, design features, environmental measurement targets) in order to generalise and increase granularity of existing data, and hence improve the understanding of energy consumption during on-site construction.

8 ACKNOWLEDGEMENTS

The authors wish to acknowledge the research funding and support from the Engineering and Physical Sciences Research Council (EPSRC) and all individuals who contributed to the research findings. Their time and participation in the interviews is greatly appreciated.

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10 APPENDIX 1-4

Appendix 1 Matrix table containing participant insights and responses to 'Driver' and 'Current Practice' on-site energy management questions during interviews

			Project Level[a]					Operational Level[a]						Director Level[a]					
	Question Topic	**Participant Insights and Responses**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Drivers	Awareness of current UK policy, legislation etc.	Broad awareness and understanding									✓	✓	✓	✓	✓	✓	✓	✓	✓
		Basic awareness and understanding	✓					✓	✓	✓									
		Limited or no awareness and understanding		✓	✓	✓	✓												
	Examples of current key drivers	Parent organisation reporting commitments	✓					✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
		Carbon Reduction Commitment (CRC)	✓					✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Dow Jones Sustainability Index								✓	✓	✓		✓		✓	✓	✓	✓
		Carbon Disclosure Project (CDP)									✓	✓	✓			✓	✓	✓	✓
	Need for capturing on-site energy consumption data	Eager to adopt more energy efficient practices to reduce fuel costs	✓					✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
		Eager to improve value and reputation							✓		✓	✓	✓	✓	✓		✓	✓	✓
		There is limited or no requirement		✓	✓	✓	✓												
Current Practice	Awareness of project life cycle energy	Broad awareness and understanding of Operational energy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Broad awareness and understanding of Embodied energy							✓				✓					✓	✓
		Basic awareness and understanding of Embodied energy	✓	✓				✓						✓		✓	✓		
		Limited or no awareness and understanding of Embodied Energy			✓	✓	✓			✓	✓	✓							
	Delivery of on-site energy management	ISO 14001 accreditation helped provide framework							✓					✓	✓	✓	✓		✓
		Responsibilities currently shared amongst multiple individuals	✓	✓					✓	✓	✓					✓	✓	✓	✓
		Current skill set for setting targets is inadequate							✓										
	Methods of communicating on-site energy management	Current communication structure ensures correct commitment and accountability							✓	✓							✓	✓	✓
		Broad awareness of new electricity tariff							✓	✓	✓	✓							✓
		Basic awareness of new electricity tariff	✓					✓					✓						
		Limited or no awareness of current electricity tariff		✓	✓	✓	✓							✓	✓	✓	✓	✓	

[a] Participants keyed to Table 1 contents.

Appendix 2 Matrix table containing participant insights and responses to 'Challenges' on-site energy management questions during interviews

	Question Topic	Participant Insights and Responses	Project Level[a]					Operational Level[a]						Director Level[a]					
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Challenges	Examples of current key challenges	Data currently insufficient for benchmarking purposes							✓	✓								✓	✓
		Most supply chain members are non-proactive and too much time is spent chasing correct information	✓	✓	✓	✓	✓		✓	✓									
		In-depth sub-metering is too costly and difficult to coordinate	✓	✓	✓			✓				✓	✓	✓	✓	✓	✓	✓	✓
		EPI Procedure is important to help reduce organisation environmental impact							✓	✓									✓
		EPI Procedure contains limited purpose and benefit		✓	✓	✓	✓												
		EPI Procedure responsibility is commonly forced upon individuals	✓	✓	✓	✓	✓		✓	✓	✓	✓				✓	✓	✓	✓
		Strong H&S emphasis is not mirrored for on-site energy management				✓	✓	✓					✓						✓
		EPI Procedure guidance is not followed and data is not reviewed before submitted		✓	✓	✓	✓						✓						
		EPI Procedure contains no detailed checks for validation purposes					✓												
		Data discrepancies between EPI Procedure and COINS			✓	✓													
		Finding time to fulfil the EPI Procedure requirements	✓	✓	✓	✓	✓	✓	✓				✓	✓					
		Lack of available staff on refurbishment projects	✓	✓										✓					
		Difficult to quantify usage between mixed power supplies for refurbishment projects	✓	✓	✓		✓							✓					

[a] Participants keyed to Table 1 contents.

Appendix 3 Matrix table containing participant insights and responses to 'Opportunities' on-site energy management questions during interviews

			Project Level[a]					Operational Level[a]						Director Level[a]					
	Question Topic	**Participant Insights and Responses**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Opportunities	Examples of current key opportunities	EPI Procedure reflects commitment towards environmental impact reduction																	✓
		Capture additional project variables to improve transparency of existing data	✓				✓	✓	✓				✓	✓	✓				✓
		Capture additional project variables to improve understanding of energy use on-site	✓			✓	✓		✓				✓	✓	✓	✓	✓		✓
		Benchmark performance to increase best practice, competency and competitiveness					✓		✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
		Benchmark performance to enable comparison and ranking per project							✓										✓
		Using red diesel generators to power on-site operations is common practice	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Earlier electrical-grid connection can improve accuracy of captured data	✓			✓			✓	✓	✓	✓	✓		✓	✓	✓	✓	✓
		Earlier electrical-grid connection can reduce red diesel consumption	✓			✓		✓	✓	✓		✓	✓			✓	✓	✓	✓
		Improved energy efficient behaviour due to new electricity tariff							✓	✓	✓	✓							✓
		Improved ability to forecast earlier electrical-grid connection due to new electricity tariff							✓	✓	✓	✓							✓
		Increased feedback to improve on-site energy management awareness and approach	✓	✓	✓		✓		✓	✓	✓	✓					✓	✓	✓

[a] Participants keyed to Table 1 contents.

Appendix 4 On-site energy management interview template, structure and questions [Not included in Paper]

ON-SITE ENERGY MANAGEMENT INTERVIEW TEMPLATE

AIM

The aim of this interview is to further investigate the key challenges and opportunities for delivering on-site energy management within UK non-domestic projects.

In particular the interview intendeds to highlight two distinctive topics: the effectiveness of the Environmental Performance Indicator's (EPI) procedure towards managing on-site energy consumption data; and in the wider context, how on-site energy management is currently perceived within the contractor.

The drivers, current practices, challenges and opportunities which are currently influencing proceedings within the investigated contractor and wider industry will be considered.

AGENDA

The following topics will be discussed:

SECTION 1	On-site Energy Management Drivers and Current Practices	(20 minutes)
SECTION 2	On-site Energy Management Challenges and Opportunities	(20 minutes)
SECTION 3	Further Thoughts	(05 minutes)
	Total Time:	(45 minutes)

Please find attached the Interview Template

SECTION 1 On-site Energy Management Drivers and Current Practices (20 minutes)

The aim of this section is to address on-site energy management drivers and current practices.

Question 1.1) What current UK policy and legislation is currently influencing practices within the wider industry and contractor?

Question 1.2) What effect have these drivers had on the contractor's current practices?

Question 1.3) What aspects of project life cycle energy are currently considered within the contractor's current practices?

Question 1.4) What practices within the contractor currently consider or influence on-site energy management?

Question 1.5) What approaches are undertaken in order to communicate the current practices affiliated to on-site energy management within the contractor?

Question 1.6) What methods are considered in order to communicate current practices affiliated to on-site energy management within the contractor?

SECTION 2 On-site Energy Management Challenges and Opportunities (20 minutes)

The aim of this section is to address on-site energy management challenges and opportunities.

Question 2.1) In your opinion, how effective is the EPI procedure in terms of managing on-site energy consumption data?

Question 2.2) In your opinion, what are the key challenges and opportunities surrounding the EPI procedure in terms of managing on-site energy consumption data?

Question 2.3) In your opinion, how could the EPI procedure be improved in order to better manage on-site energy consumption data?

Question 2.4) In your opinion, what are the key challenges currently influencing the uptake of on-site energy management practices within the wider industry?

Question 2.5) In your opinion, how could on-site energy management be better managed throughout the industry?

SECTION 3 Further Thoughts (5 minutes)

TOTAL 45 minutes

APPENDIX B ADDRESSING EMBODIED ENERGY (PAPER 2)

Full Reference

Davies, P.J., Emmitt, S., Firth, S.K., Kerr, D. (2013b) Addressing embodied energy from a contractor's perspective. *Sustainable Building Conference SB13*, 3-5 July, Coventry.

Abstract

Despite the need for enhanced energy efficiency within the UK non-domestic sector, it seems limited effort is currently directed towards reducing embodied energy as opposed to operational energy levels. Embodied energy relates to the indirect and direct energy inputs required for various forms of construction. Contractors have a vested interest within embodied energy performance due to their significant involvement within project procurement, pre-construction and on-site construction activities. The key challenges and opportunities are investigated for addressing embodied energy levels within UK non-domestic projects from a contractor's perspective. A case study containing two desk studies is presented. The first desk study reviewed the relative significance of individual life cycle energy phases within existing LCA studies, whereas the second desk study appraised the practical challenges within a large UK principal contractor's on-site current practices to support an embodied energy assessment. Weaknesses are identified within existing LCA studies which makes it difficult to understand the significance of individual life cycle energy phases and help formulate energy reduction targets for future projects. Findings identified at present the fragmented nature of data presented within LCA studies and the contractor current practices limits project decision makers to fully understand the implications of potential design or material changes in terms of total project life cycle energy.

Keywords

Embodied energy, contractor, challenges, opportunities, life cycle assessment, current practices.

Paper Type – Conference Paper

Referred Name – Paper 2

1 INTRODUCTION

There is a current requirement within the UK non-domestic sector to enhance energy efficiency. The sector is accountable for 18% of the UK's total CO2 emissions (operational and embodied) (BIS 2010; Carbon Connect 2011). Project life cycle energy is derived from operational energy and embodied energy (Dixit et al. 2012). At present there is limited data which supports the capture and assessment of embodied energy throughout the construction process (Van Ooteghem and Xu 2012). A contractor is typically responsible for pre-construction and on-site construction activities; all of which can influence project life cycle energy (Li et al. 2010). Traditionally clients are focused towards reducing project operational energy use, though it seems contractors have a vested interest within embodied energy levels due to their role within project procurement. It appears improved knowledge and opportunities to reduce overall project life cycle energy could be obtained if energy consumption per individual life cycle phase and the relationship between them is reviewed (Optis and Wild 2010; Ramesh et al. 2010). Therefore, this research aims to investigate the key challenges and opportunities for addressing embodied energy levels within UK non-domestic projects from a contractor's perspective.

2 ROLE OF THE CONTRACTOR

The construction of a building includes activities such as planning, design, on-site construction, operation and maintenance. Generally, the contractor is responsible for pre-construction (i.e. selecting construction methods) and on-site construction activities (i.e. installation of building materials and services) (Li et al. 2010). Though, the role of the contractor and their influence over design varies according to the particular project procurement method. During the 'traditional method' of procurement the architect is expected to have completed the design before the contractor gets involved, leading to detailed prescriptive specifications being produced that limits the flexibility of the contractor to involve their own supply chain. In contrast, the 'design-and-build method' provides the contractor with opportunities to involve their own supply chains earlier during design development and 'value engineer' designs to reduce potential project design risk (Latham 1994; Hamza and Greenwood 2009).

3 DEFINING AND ASSESSING EMBODIED ENERGY

There is an increasing need to assess the environmental impact of projects through a life cycle perspective. Operational energy relates to energy use during building occupier activity, whereas embodied energy relates to energy use within the extraction, manufacture, transportation and assembly of raw materials required for construction, renovation, maintenance, refurbishment, modification and demolition (Dixit et al. 2012; RICS 2010). Embodied energy can be separated into initial, recurring and demolition embodied energy. In particular interest of a contractor, initial embodied energy includes energy use during material (i.e. procurement of raw materials), transportation (i.e. transport of project resources such as materials, plant and equipment, and operatives), and construction (i.e. on-site assembly) life cycle phases up to project practical completion (Cole and Kernan 1996; Chen et al. 2001).

Generally, challenges and opportunities to tackle project life cycle energy are highlighted through a Life Cycle Assessment (LCA) which is defined as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (British Standard 2006:2). Traditionally embodied energy is expected to represent a smaller proportion of project life cycle energy as opposed to operational energy, though some studies have recognised the proportional relationship between operational and embodied energy levels can differ depending on certain project characteristics (i.e. project type, location and environmental agenda) (Thormark 2002; Gustavsson et al. 2010; Ramesh et al. 2010). Capturing embodied energy data appears difficult namely due to project nature, timescale and complexity; hence currently there is no standardised method for capturing data throughout the whole construction process (Langston and Langston 2008; Van Ooteghem and Xu 2012). Practitioners commonly rely on project data derived from contractor and supply chain current practices in order to assess embodied energy levels (Kofoworola and Gheewala 2009; Chang et al. 2012).

4 DRIVERS FOR CONTRACTORS

4.1 POLICY AND LEGISLATIVE

The European Union (EU) and the UK government have recently established numerous measures intended to drive Greenhouse Gas (GHG) (namely CO2) and energy consumption reduction within the UK non-domestic sector. The EU Renewable Energy Directive, the Energy Performance of Buildings Directive (EPBD), the UK Low Carbon Transition Plan (LCTP), the Climate Change Act 2008, and the UK Building Regulations are to name a few (Legislation 2008; DECC 2009; DIAG 2011). However, these measures are primarily focused towards reducing operational impacts, overlooking embodied impacts. Nonetheless, recent evidence suggests a change in focus is likely in the future as operational impacts are expected to reduce over time owing to increased energy efficiency and effective building design, thus increasing the significance of embodied impacts (Fieldson and Rai 2009; BIS 2010; Rai et al. 2011).

4.2 FINANCIAL AND BUSINESS

Due to future energy price rises UK contractors are more conscientious of the need to reduce energy demand and improve the energy efficiency of their operations (SFfC, 2010). The introduction of carbon taxation through the Carbon Reduction Commitment (CRC) Energy Efficient Scheme has emphasised that the cost of poor energy efficiency is likely to escalate in the future (Carbon Connect, 2011). The CRC enables contractors to consider a proportion of project life cycle energy due to the capture and assessment of fuel consumption on-site. Moreover, in recent years, contractors have focused efforts towards reducing their CO2 and energy consumption levels and encouraging supply chains to follow suit in order to ascertain repeat business (SCTG 2002; Bansal and Hunter 2003; BIS 2010).

5 CHALLENGES FOR CONTRACTORS

5.1 FINANCIAL AND BUSINESS

Seemingly the environmental practices currently undertaken by project decision makers are insufficient towards reducing CO2 emissions (Morton et al. 2011) and it seems environmental practices are only adopted if they are financially viable (Sodagar and Fieldson 2008). During a price sensitive market, manufacturers have little incentive to develop products, materials or renewables which are vastly more efficient than their competitors (Hinnells 2008). Nonetheless, due to high energy prices and the lack of legislative measures surrounding renewable technologies, improved energy efficiency from building services is more economically attractive to a client than a wide application of renewables (Tassou et al. 2011). Even though embodied impacts can increase due to the installation of energy efficient building services, Halcrow Yolles (2010) argued embodied impacts cannot be justified as a reason not to install renewable technologies.

5.2 DESIGN AND TECHNICAL

Currently there are multiple schemes and standards available intended to support environmental reporting and management, though the wide variations within these measures make it difficult to evaluate the environmental impact of key project stakeholders (IEMA 2010; Carbon Connect 2011). The inconsistency has created unfamiliarity throughout the supply chain as designers are unsure about the impact of their decisions (BIS 2010). Hence, there is a clear need for improved awareness of the implications of building design towards project life cycle impacts. It seems the choice of building material can significantly influence project embodied and operational impacts (Halcrow Yolles 2010).

At present within the UK construction industry it seems there is a deficiency of available, robust project data which provides awareness of how energy is consumed within different building types across various project life cycles (Dixit et al. 2012). Buildings themselves provide the biggest obstacle as they are complex in terms of form, function, life span, and end user requirements (Scheuer et al. 2003; Van Ooteghem and Xu 2012).

6 OPPORTUNITIES FOR CONTRACTORS

6.1 FINANCIAL AND BUSINESS

Contractors are influential towards promoting sustainable development due to their responsibility and impact on society and the environment. Despite compliance with environmental regulation being portrayed as a costly action, contractors can obtain enhanced environmental protection, increased competitiveness and improved environmental performance (SFfC 2008; Tan et al. 2011).

Globalisation has encouraged contractors to create vast networks of suppliers and distributors intended to improve the efficiency of material, labour and energy use. Increased cooperative relationships with suppliers can enable contractors to increase their ability to manage environmental issues more effectively; empowering contractors to improve quality and become future industry leaders (Lee 2010; Parmigiani et al. 2011). If contractors are more forceful towards encouraging clients to adopt environmental practices this could support enhance stakeholder relationships, company profile, reputation, and competitive advantage (Hirigoyen et al. 2005; Morton et al. 2011). Moreover, due to contractor involvement within project procurement multiple advantages can be obtained from reducing project transportation requirements, such as: reduced fuel and delivery costs; increased delivery reliability; reduced cost for parking; and increased profitability (BRE 2003).

6.2 DESIGN AND TECHNICAL

Previous research has highlighted the importance of the design stage when tackling the project embodied impacts (Scheuer et al. 2003; Goggins et al. 2010). The design stage provides project decision makers with an opportunity to consider both embodied and operational impacts through the principle of bioclimatic design and selection of low carbon materials and energy efficient building services (Halcrow Yolles 2010; Rai et al. 2010). A reduction in embodied energy can be obtained through the incorporation of waste minimisation, reduced material use, increased recycled content and specifying materials with low embodied impact per weight (Harris 1998; Chen et al. 2001; Rai et al. 2010). The choice of material can not only influence embodied impacts, but also construction methods, operational use, maintenance cycles and building life span (Fieldson and Rai 2009).

If a contractor can manage the construction process in a safe, efficient and effective manner, this will provide opportunities to save time and cost affiliated to fuel usage and logistics (Sodagar and Fieldson 2008). The efficient use of plant and equipment during on-site construction can provide savings in fuel use, cost and improve site safety. An earlier connection to the national electricity grid can provide savings in fuel use, security costs, space required for generators, and improve site safety (RICS 2008; Ko 2010). In addition, a contractor can reduce temporary site accommodation energy requirements if accommodation is well designed, positioned and managed. The use of energy efficient site accommodation can increase operative comfort levels, productivity and reduce absenteeism (Ko 2010).

7 METHOD

The research applied a case study methodological approach consisting of two desk studies. The first desk study was based upon a review of existing LCA studies which focused towards embodied energy assessment. This review aimed to highlight the extent of existing knowledge surrounding the relative significance of individual life cycle energy phases. The second desk study was undertaken within a large principal contractor based in the UK. A series of current practices employed by the contractor during the construction phase of a UK non-domestic sector project were appraised post-construction. This appraisal aimed to determine the practical challenges surrounding the contractor's current practices towards potentially supporting an embodied energy assessment within future projects. The explored UK non-domestic sector project was a recently finished design and build industrial warehouse located within the south of England.

8 RESULTS AND DISCUSSION

8.1 REVIEW OF EXISTING LCA STUDIES

It was previously highlighted improved knowledge and opportunities to reduce overall project life cycle energy could be obtained if energy consumption per individual life cycle phase and the relationship between them is reviewed (Optis and Wild 2010; Ramesh et al. 2010). Hence, attempts were made to highlight the relative significance of individual life cycle energy phases and identify areas of improvement within industry knowledge.

A total of 16 existing LCA case studies which focused towards embodied energy assessment were reviewed. These studies varied in terms of project scope, type and geographical location. Attempts were made to focus on non-domestic sector projects although a significant proportion of existing LCA studies have assessed residential buildings (Adalberth 1997; Fay et al. 2000; Chen et al. 2001; Mithraratne and Vale 2004) hence this data was also considered to potentially highlight the significance of project type. Table 1 illustrates the impact of total project or specific construction materials in terms of individual project life cycle phases (i.e. material, transportation, and construction), total embodied energy, or total life cycle energy levels (i.e. embodied plus operational energy). Evidently, limited studies illustrated impacts relative to individual project life cycle phases. Although the review did highlight the impact of transportation and construction energy as small in comparison to material related energy, as supported by Adalberth (1997), Cole (1999), Chen et al. (2001) and Gustavsson et al. (2010). Each study differed significantly in terms of parameters such as the selection of system boundaries, calculation methods and data sources. Hence it is difficult to understand or even compare data amongst similar project types, which is an issue previously highlighted by Optis and Wild (2010) and Dixit et al. (2012). Nonetheless, a wide range of inconsistent values were used to portray the significance of embodied energy relative to total project life cycle energy across assorted project types. For instance, Scheuer et al. (2003) suggested embodied energy represents 2.2% of total project life cycle energy for an educational building within USA whereas Huberman and Pearlmutter (2008) reported embodied energy represents 60% of total project life cycle energy for an apartment building within Israel. Overall, the varied format of data presented within the existing LCA case studies (Goggins et al. 2010) seems to limit the use of existing knowledge to formulate robust benchmarks and targets for future energy reduction within construction projects, which is a impending requirement supported by BIS (2010).

8.2 APPRAISAL OF CONTRACTOR CURRENT PRACTICES

In line with existing LCA studies, contractor current practices which provided information suitable to assess the embodied energy performance of the project (material characteristics, transport vehicle type, transport distance travelled, on-site fuel type and consumption etc.) were appraised. It was discovered the contractor used a programme of works (PoW) in order to help coordinate the development and delivery of the project. Although, there was no direct link between the construction activities and the sub-contractors responsible for their completion within the PoW. Hence, as all other current practices captured data relative to sub-contractors not construction activities, it seems the PoW provides limited use to help coordinate the capture of data relative to certain construction activities. Additionally, the contractor used a plant register in order to document and maintain the operational performance of on-site plant and equipment. The information captured from the sub-contractors, which used on-site plant and equipment, varied significantly in terms of content, detail, legibility and terminology. It was discovered there was no clear correlation between the plant and equipment used and the specific construction activities undertaken by the sub-contractors. Moreover, the bill of quantities (BoQ) and design drawings were used by the contractor to coordinate project cost and design and also provide information on material characteristics and specification. Although, it appeared the material characteristics within these current practices was displayed in no consistent format (i.e. mm, m, m2, m3, tonne, kg) which could be used to compare against data within existing LCA studies.

Reference	MAT[1]	TRAN[1]	CON[1]	Total EE[1]	Total OP[1]	Pro Type	Results per…	Location	Add Notes
Adalberth (1997)				15% LCE		Dwelling	Total Project	Sweden	Equal 7 years OP
	10% LCE	<1% LCE	1% LCE		85% LCE	Dwelling	Total Project	Sweden	50 year life span
Chang et al. (2012)	90% EE	4% EE	6% EE	6.3 GJ/m^2		Educational	Total Project	China	Process-based
Chen et al. (2001)	90.7% EE	7.4% EE	1.6% EE			Residential	Total Project	China	40 year life span
Cole (1999)			8-20 MJ/m^2			Multi Office	Timber Frame	Canada	
			3-7 MJ/m^2			Multi Office	Steel Frame	Canada	
			20-120 MJ/m^2			Multi Office	Conc' Frame	Canada	
Cole and Kernan (1996)				4.54 GJ/m^2		Multi Office	Timber Frame	Canada	
				5.13 GJ/m^2		Multi Office	Steel Frame	Canada	
				4.79 GJ/m^2		Multi Office	Conc' Frame	Canada	
		5-8% LCE				Multi Office	Conc' Frame	Canada	50 year life span
Crawford (2008)				10.1 GJ/m^2		Commercial	Total Project	Australia	Process-based
				8.0 GJ/m^2		Commercial	Total Project	Australia	Process-based
				6.9 GJ/m^2		Residential	Total Project	Australia	Process-based
Fay et al. (2000)				14.1 GJ/m^2		Residential	Total Project	Australia	Primary Energy
Gustavsson et al. (2010)				975kWh/m^2		Apartment	Timber Frame	Sweden	
Huberman …(2008)				60% LCE	40% LCE	Apartment	Total Project	Israel	50 year life span
				8.0 GJ/m^2		Apartment	Total Project	Israel	
Kofoworola ...(2009)				15% LCE	81% LCE	Office	Total Project	Thailand	50 year life span
	16.8% LCE	0.6% LCE				Office	Total Project	Thailand	0.4% demolition
				6.8 GJ/m^2		Office	Total Project	Thailand	
Mithraratne …(2004)				4.4-5.0 GJ/m^2		Dwelling	Total Project	New Zea'	
				34% EE		Dwelling	Floor	New Zea'	100 year life
				43% EE		Dwelling	Walls	New Zea'	100 year life
				38% EE		Dwelling	Roof	New Zea'	100 year life
Monahan …(2011)				5.7-8.2 GJ/m^2		Dwelling	Total Project	UK	Primary Energy
Rai et al. (2011)	31% EE					Warehouse	Steel Frame	UK	25 year life span
	17% EE					Warehouse	External Wall	UK	25 year life span
Scheuer et al. (2003)	2% LCE	0.1% LCE	0.1% LCE	7.0 GJ/m^2		Educational	Total Project	USA	75 year life span
				2.2% LCE	97.7% LCE	Educational	Total Project	USA	0.2% demolition
Thormark (2002)				40% LCE	60% LCE	Apartment	Total Project	Sweden	50 year life span
Van Ooteghem …(2012)				9% LCE	91% LCE	Retail	Total Project	Canada	50 year life span
				52% EE		Retail	Roof	Canada	
				9% EE		Retail	Frame	Canada	
				13% EE		Retail	Foundations	Canada	

[1] LCE, Project Life Cycle Energy (cradle-to-end of life); EE, Embodied Energy.

Table 1 Review of 16 existing LCA studies

The contractor used two versions of sign-in sheets; one version was used to capture operative man-hours and man-days per sub-contractor whereas the other version was used to capture visitor and material transport to and from site. Both versions captured a varied degree of complete, valid information. It could be argued the mixed success of the sign-in sheets was due to their respective locations. Both sheets were located within the contractor's on-site accommodation though, as opposed to the operative entrance, the material delivery entrance was the other side of the site. Furthermore, the contractor used a unique management procedure intended to capture and assess fuel consumption during on-site construction. It was discovered the data captured from the sub-contractors was not examined in the same manner as the contractor's personal data (i.e. limited fuel delivery tickets provided). Hence, vast ambiguity surrounding sub-contractor data was discovered in terms of the quantity of fuel delivered, when fuel was delivered and how much fuel was consumed during periodic intervals.

Overall, based upon the type and level of data captured within the current practices it seems difficult at present for the contractor to truly evaluate the embodied impact of different aspects of a building. It appears the inconsistencies within the data make it difficult for any decision maker to accurately understand the significance of potential design or material changes, an issue acknowledged by BIS (2010) and Halcrow Yolles (2010). In addition the lack of a clear relationship between data, sub-contractors and construction activities seems to limit the possibility of formulating energy reduction targets for future projects (BIS 2010).

9 CONCLUSIONS

The research investigated the key challenges and opportunities for addressing embodied energy levels from the perspective of a large principal contractor based in the UK. The initial desk study highlighted the need for improved consistency within LCA studies in order to better understand the relative significance of individual life cycle energy phases and the relationship between them. As noted by literature, this could potentially highlight improved knowledge and opportunities to reduce total project life cycle energy. Though, due to the inconsistent research approaches and data format, it seems difficult at present to use knowledge within existing LCA case studies to help formulate robust benchmarks and targets for future energy reduction within construction projects.

From the findings it seems likely contractors could potentially lead the industry towards improved embodied energy awareness simply due to their significant involvement within project procurement. However, from the second desk study it appears significant changes are required to contractor current practices in order to improve their overall usefulness, in particular: linking sub-contractors to construction activities within the programme of works; maintaining consistent terminology within the plant register; capturing improved transportation data within sign-in sheets.

Evidently, it seems the fragmented nature of data present within LCA studies and the contractor current practices makes it difficult at present for project decision makers to fully understand the implications of potential design or material changes in terms of total project life cycle energy. Hence, considering the research findings and current knowledge within literature, there appears to be limited understanding of the possible implications which could occur from targeting improved embodied energy efficiency throughout different project life cycle phases. Attempts to reduce embodied energy of a particular building aspect (i.e. frame, roof, external walls) could lead to material transportation difficulties and changes in the impact of different project life cycle phases. Design changes intended to provide clients with improved operational energy efficiency could impact a contractor's control over procurement and construction methods in addition to overall building maintenance cycles and life span. Nonetheless, it seems the current lack of UK legislative measures is impeding embodied energy consideration throughout the construction process.

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APPENDIX C CHALLENGES FOR CAPTURING AND ASSESSING (PAPER 3)

Full Reference

Davies, P.J., Emmitt, S., Firth, S.K. (2014) Challenges for capturing and assessing initial embodied energy: a contractor's perspective. *Construction Management and Economics*, 32(3), 290-308.

Abstract

Initial embodied energy includes energy use during material, transportation, and construction life cycle phases up to project practical completion. Contractors have an important role to play in reducing initial embodied energy levels due to their significant involvement in pre-construction and on-site construction activities. Following an extensive literature review a comprehensive framework was designed to highlight the significance of initial embodied energy levels relative to specific construction packages, activities and sub-contractors. This framework was then applied to a new UK industrial warehouse project using a case study approach. Capturing information from a live project during the entire construction phase helped highlight the practical challenges inherent when capturing and assessing initial embodied energy levels. A series of contractor current practices were reviewed to determine their compliance with the framework requirements. The findings revealed that the ground and upper floor, external slab and frame were the most significant construction packages in terms of embodied impacts. Many challenges embedded within the contractor's current practices in terms of data detail, legibility, and terminology was also revealed. The framework provides a practical approach for initial embodied energy assessment which can readily be adopted by contractors to help highlight opportunities to increase efficiency.

Keywords

Embodied energy, life cycle, contractor, construction, transport, materials.

Paper Type – Journal Paper

Referred Name – Paper 3

1 INTRODUCTION

There is a growing pressure on contractors to manage the life cycle performance of a project, part through schemes such as BREEAM (Building Research Establishment Environmental Assessment Method) and part due to pressures placed on them by clients. Project life cycle energy is derived from operational and embodied energy impacts. Operational energy relates to the energy consumed during building occupier activity, whereas embodied energy relates to the indirect (energy used during extraction and manufacture of raw materials) and direct energy inputs (energy used to assist transportation and installation of materials) required for various forms of construction (Cole, 1999; Dixit et al., 2010; Davies et al., 2013). Typically embodied energy represents the smallest proportion of project life cycle energy (Gustavsson et al., 2010), although it is still an important factor. As operational energy efficiency increases due to improved energy efficient design, embodied energy will become a more significant part of project life cycle energy (Fieldson and Rai, 2009).

Embodied energy can be separated into initial, recurring and demolition embodied energy. Initial embodied energy is of particular interest to a contractor because they are responsible for pre-construction activities (i.e. specifying construction methods, plant and equipment, and ancillary materials) as well as on-site construction activities (i.e. site preparation and installation of structure, envelope, mechanical and electrical services, and interior finishes) all of which can harm the environment (Kofoworola and Gheewala, 2009; Li et al., 2010) and impact project life cycle energy.

Opportunities to capture and address project life cycle energy are typically identified through a Life Cycle Assessment (LCA). Previous LCA studies have assessed varied project life cycle phases across assorted project types. For example, Langston and Langston (2008) developed an economic input-output (I-O) based hybrid method to assess the initial embodied energy performance of 30 commercial and residential projects. Others have also developed process-based hybrid methods to address certain initial embodied energy impacts, such as Bilec et al. (2010) and Chang et al. (2012). Inherent differences within these studies in terms of system boundary, calculation method and data source selection (Optis and Wild, 2010; Dixit et al., 2012) forces LCA practitioners to assume or even ignore certain life cycle impacts; all of which questions the accuracy, validity and usefulness of existing data (Treloar et al., 2000; Ding and Forsythe, 2013).

Another criticism of the extant LCA studies is that they have not explored a practical approach for the assessment of initial embodied energy levels which could readily be adopted by project stakeholders. Similarly, the significance of construction packages and activities in terms of individual life cycle phases (i.e. material, transportation, construction impacts) has not been adequately addressed. However, recent guidance documents BIS (2010) and Ko (2010) have highlighted the need for improved project life cycle energy data within the UK non-domestic sector to help project stakeholders benchmark performance and develop targets and incentives for increased efficiency. Langston and Langston (2008) claimed that an accurate, practical, approach is required which can routinely be applied by project stakeholders to assess and better understand project life cycle energy. Such an approach may help identify improved opportunities to reduce overall project life cycle energy through the examination of individual life cycle phases (Sodagar and Fieldson, 2008; Optis and Wild, 2010).

The construction process includes the "transport, enabling works, assembly, installation, and disassembly activities" (Ko, 2010:11) which are required to facilitate construction. The process is responsible for significant natural resource and energy consumption (Ortiz et al., 2009). Currently there is very little research that supports the quantification and management of embodied energy relating to the construction process (Bilec et al., 2006; Li et al., 2010; Davies et al., 2013). Due to the requirements of BREEAM, contractors are already expected to capture process-based data for the transportation and construction phases, as well as data to assess the material phase impacts of specific construction packages (BRE, 2011). The aim was to investigate the practical challenges for capturing and assessing initial embodied energy levels within the UK non-domestic sector from a contractor's perspective. A thorough literature review led to the development of a practical framework to address the inherent weaknesses common to LCA studies. The framework was then applied to a live construction project to enable the capture of original data; a process which also revealed the practical challenges inherent in capturing data from live projects.

2 PROJECT LIFE CYCLE ENERGY

Project life cycle energy is derived from operational and embodied energy impacts. Life cycle operational energy is derived from the energy used during building occupier activity whereas life cycle embodied energy is derived from initial, recurring and demolition embodied energy. Initial embodied energy includes energy use during material (i.e. extraction and manufacture of raw materials), transportation (i.e. transport of materials, plant and equipment, and operatives), and construction (i.e. on-site assembly) life cycle phases up to project practical completion. Recurring embodied energy is the energy used during refurbishment, renovation and maintenance whereas demolition embodied energy is the energy used during on-site deconstruction and disassembly (Cole, 1999; Dixit et al., 2010; Davies et al., 2013). Figure 1 illustrates the various life cycle phases and activities which impact project life cycle performance. There has been strong emphasis within previous research towards assessing and reducing operational energy levels as this phase typically represents a greater proportion of project life cycle energy in comparison to embodied energy (Gustavsson et al., 2010). In a study which examined the life cycle energy performance of a retail building in Canada during a 50 year life span Van Ooteghem and Xu (2012) highlighted operational and embodied impacts as 91% and 9% of the total respectively. However, some studies have highlighted the importance of embodied energy. Pearlmutter et al. (2007) assessed the energy consumption associated with building materials used to construct a residential building within Israel whereby, during a 50 year life span, operational and embodied impacts represented 15% and 85% of the total respectively. Nonetheless, previous studies have identified that focus towards reducing the impact of certain project life cycle phases could lead to changes in the contribution of different phases (Blengini and Di Carol, 2010; Davies et al., 2013). For example, attempts to reduce operational heating requirements through super-insulated windows and walls could lead to increased material and transportation phase impacts. Hence, improved understanding and opportunities to reduce overall project life cycle energy could be obtained if impacts derived from individual life cycle phases and the relationship between them is considered (Sodagar and Fieldson, 2008; Optis and Wild, 2010).

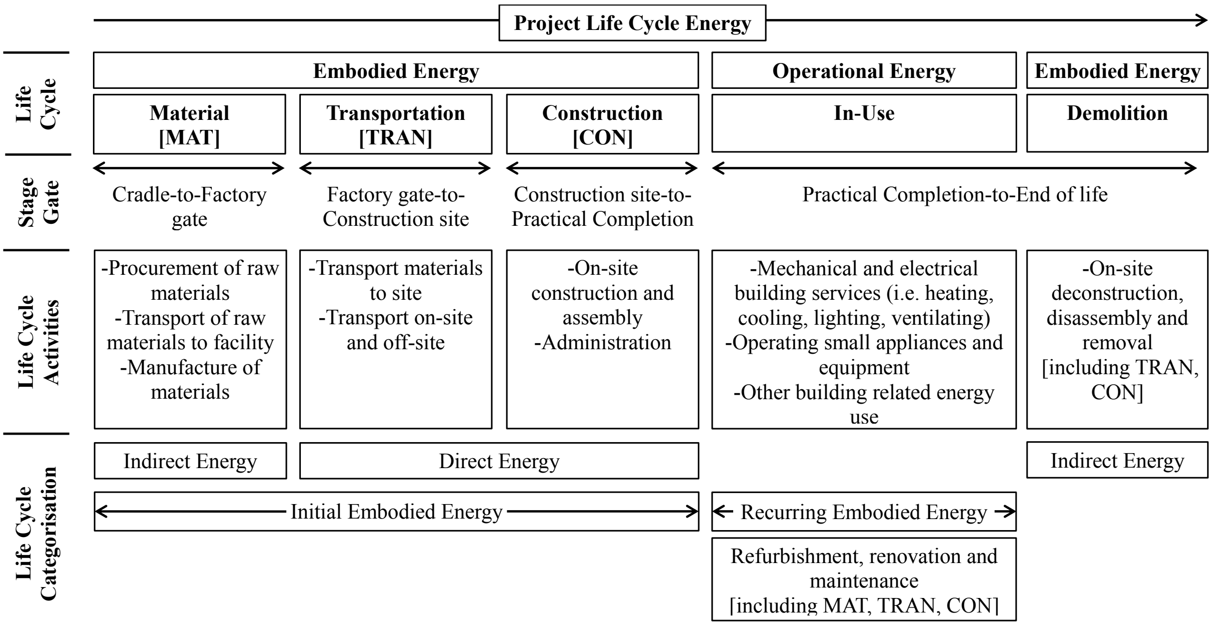

Figure 1 Material project life cycle energy (after Cole, 1999; Dixit et al., 2010; Davies et al., 2013)

3 LIFE CYCLE ASSESSMENT (LCA)

A LCA is defined as a *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"* (British Standard, 2006:2). LCA methodology is based upon the principles addressed by the International Standards of series ISO 14040 which includes four distinctive stages. Firstly, the scope and goal of the LCA is defined by highlighting the purpose, audience and system boundaries. Secondly, a life cycle inventory (LCI) analysis is undertaken which consists of collecting data from all key input and outputs necessary to meet the goal of the LCA (e.g. energy use). Thirdly, a life cycle impact assessment is undertaken which evaluates the potential environmental impacts and estimates the resources used within the modelled system. Finally, the overall findings are reviewed in order to reach definitive conclusions and produce recommendations (British Standard, 2006; Ortiz *et al*., 2009).

LCA can be used to assist decision-makers for the purpose of strategic planning, help the selection of measurement techniques and indicators of environmental performance, and aid organisation marketing strategies through environmental claims (Sodagar and Fieldson, 2008; Ortiz *et al*., 2009; Doran and Anderson, 2011). However, undertaking a LCA is a very complex, expensive and time consuming endeavour. LCA's are industry specific and applying a LCA to construction is challenging because construction projects involve many, complex processes whereby multiple assumptions are commonly required (Treloar *et al*., 2000; Van Ooteghem and Xu, 2012; Basbagill *et al*., 2013).

3.1 LCA SYSTEM BOUNDARIES

The selection of system boundaries (i.e. first stage) for a LCA helps define the number of inputs which are considered within an assessment. A well-defined boundary ensures practitioners do not waste time collecting data beyond the research scope and improves the usefulness of captured data (Crawford, 2008; Optis and Wild, 2010; Dixit *et al*., 2012). Nonetheless, due to practitioner interpretation and flexibility in designing system boundaries, the comparison of two LCA's of the same material or product is not necessarily a straightforward process (Kofoworola and Gheewala, 2009).

3.2 LCA CALCULATION METHODS

The life cycle inventory (LCI) analysis (i.e. second stage) is a reflection of the general quality and successes of an assessment. The LCI quantifies the input and output flows for a particular product or process and provides the foundation to support the impact assessment (i.e. third stage) (Scheuer *et al*., 2003; Crawford, 2008). In general, there are three LCI methods which are commonly used by LCA practitioners; process, economic input-output (I-O), and hybrid-based method (Crawford, 2008; Bilec *et al*., 2010; Chang *et al*., 2012).

3.2.1 PROCESS-BASED METHOD

The process-based method is the most widely used LCI method and involves the systematic analysis of inputs and outputs within a process. The energy requirement of a particular process or product is calculated from all material, equipment and energy inputs into the process (Emmanuel, 2004; Pearlmutter *et al*., 2007). Despite the potential for high quality, reliable results Stephan *et al*. (2012) acknowledged this method suffers from system boundary truncation. Crawford (2009) applied and compared multiple LCI methods to a range of building types within Australia and discovered that the truncation error resembled 66% for a particular commercial building in comparison to alternative LCI methods.

3.2.2 INPUT-OUTPUT-BASED METHOD

The economic input-output (I-O) based method is a top-down technique which focuses on financial transactions through the use of input-output tables to determine the energy intensity of economic sectors. The method highlights inter-relationships between different sectors and quantifies the energy requirements of a particular product based upon its price (Emmanuel, 2004; Stephan *et al*., 2012). The use of I-O data can improve system boundary completeness of life cycle study (Crawford, 2008) although key limitations surround the age of the input-output tables, the use of national averages, and the conversion from economic data to energy data (Lenzen, 2001; Treloar *et al*., 2001).

3.2.3 HYBRID-BASED METHOD

The hybrid-based method combines features of both process and I-O based methods. Typically, the method uses the principles of a process-based method until gaps emerge within data which are filled by the use of an I-O based method. For example Kofoworola and Gheewala (2009) and Chang *et al*. (2012) used an I-O based method to calculate the environmental impact of the material manufacture phase and a process-based method to assess the environmental impact of the transportation and construction phases.

3.3 LCA DATA SOURCES

Databases are designed to help practitioners understand and quantify project life cycle impacts. The Inventory of Carbon and Energy (ICE) is portrayed as one of the most standardised, publically available embodied energy and carbon datasets available within UK construction (Hammond and Jones, 2006). Previous research such as Fieldson and Rai (2009) used the dataset to identify the embodied impact of the internal finishes of a UK retail building whereas Rai et al. (2011) used the dataset to highlight the embodied impact of specific construction packages and materials included within a UK industrial warehouse. Principally, materials included within the database are assessed from a cradle-to-factory gate perspective and based upon publically available secondary sourced data (e.g. journal papers, technical reports, Environmental Performance Declaration's) (BSRIA, 2011). However previous studies have indicated the use of incomplete, non-validated secondary source data can lead to uncertainty and variability in results (Peereboom *et al*., 1998). Hence, there is a need for a standardised approach for capturing and assessing embodied impacts in order to develop legitimate, high-quality data to better support the decision making process (BIS, 2010; Dixit *et al*., 2012; Van Ooteghem and Xu, 2012).

3.4 LCA ASSUMPTIONS

To undertake a LCA, practitioners commonly rely on contractors, sub-contractors or material suppliers to provide primary data in the form of design drawings, performance specifications, bill of quantities, on-site measurements and records (Scheuer *et al*., 2003; Kofoworola and Gheewala, 2009). However, due to data complications, sensitivity issues and the complex nature of construction projects practitioners commonly assume or even ignore certain data. For example, Gustavsson *et al*. (2010) assumed the energy consumed during the construction phase of an apartment building (i.e. 80 kWh/m^2), Cole (1999) assumed the distance operatives travelled to and from during the transportation phase of an office building (i.e. 50 km), and a recent industry publication Halcrow Yolles (2010) ignored the transportation and construction phase impacts all together during the assessment of three UK office buildings.

4 METHODOLOGY

The research comprised a case study methodological approach within a large principal contractor based in the UK, consisting of a desk study and quantitative analysis of original data. The contractor provided a suitable sample as they have a fundamental role during project life cycle and are overall responsible for compliance with current forms of environmental measurement such as BREEAM.

The case study project was a large design and build temperature controlled distribution centre (i.e. industrial warehouse) located in the south of England. The project contained a three storey office, two pod offices and three internalised temperature controlled chambers for ambient (10 ºC), chilled (5 ºC) and frozen (-23ºC) operating and storage use. The main building comprised: prefabricated steel structure; composite roof and cladding panels; precast concrete retaining wall; glazed façade (for the offices); 50 dock levellers; multiple air source heat pumps for heating and cooling; and a rainwater harvesting unit to offset toilet flushing and external vehicle wash. A sample of construction packages, activities and sub-contractors were investigated in detail (Table 1) due to their relative contribution towards project value, project duration, operative numbers and quantity of materials used.

4.1 DESK STUDY

A comprehensive review of literature helped to inform the design of a framework, which addressed weaknesses common to LCA studies. The framework comprised of five key sections; principles, indicators, structure, equations, and alignment. Current practices employed by a contractor during the construction phase of a UK non-domestic sector project were reviewed (e.g. programme of works, plant register, sign-in sheets) to determine whether the practices could provide the necessary data to fulfil the requirements of the framework.

4.1.1 FRAMEWORK PRINCIPLES

The framework was based upon the principles of a hybrid-based method whereby a mixture of calculation methods were used to assess the initial embodied energy levels of the project. The framework supported the capture and use of primary and secondary sourced data. A process analysis method was used to capture and assess the energy inputs during the transportation and construction phases whereas secondary source data derived from the ICE material database was used to evaluate the energy inputs during the material phase. Characteristics of the construction materials (i.e. measurements) were obtained from primary data sources.

Table 1 List of investigated construction packages, activities and sub-contractors

Act Ref.	Sub-contractor Name	Construction Package	Construction Activity	Notes
Act 0	Main Contractor	Project Management	Project Management	
Act 1a	Earthworks	Earthworks	Hardcore	Aggregate (existing)
Act 1b	Earthworks	Earthworks	Hardcore	Aggregate (import)
Act 1c	Earthworks	Earthworks	Soil	Common Earth
Act 2a	Foundations	Foundations	Vibro Compaction Piles	Aggregate
Act 3a	Groundworks	Groundworks	Kerb and Edgings	Battered
Act 3b	Groundworks	Groundworks	Kerb and Edgings	Trief / Titan
Act 3c	Groundworks	Groundworks	Drainage	Land / Storm (HDPE)
Act 3d	Groundworks	Groundworks	Drainage	Precast Concrete
Act 3e	Groundworks	Groundworks	Drainage	Gatic
Act 3f	Groundworks	Groundworks	Concrete (Pile Caps, Column Casing etc.)	In-situ Concrete
Act 4a	Frame	Frame	Steel Columns	
Act 4b	Frame	Frame	Steel Beams	Inc. Bracing, Ties
Act 5a	Mechanical and Ele’	Mechanical and Ele’	Electrical Services	Wire
Act 5b	Mechanical and Ele’	Mechanical and Ele’	H/L HV and HWS Insulation	Pipe Work / Duct Wrap
Act 5c	Mechanical and Ele’	Mechanical and Ele’	Mechanical Ductwork	
Act 5d	Mechanical and Ele’	Mechanical and Ele’	Mechanical Pipework	Gas Pipe
Act 5e	Mechanical and Ele’	Mechanical and Ele’	Mechanical Pipework	Water Pipe
Act 6a	External Walls	External Walls	Composite Wall Cladding	
Act 6b	External Walls	Roof	Composite Roof Cladding	
Act 7a	Retaining Walls	Retaining Walls	Precast Concrete	
Act 7b	Retaining Walls	Pro-Wall	Precast Concrete	Dock Lintels, Back and Side Walls
Act 8a	Sprinklers	Sprinklers	Pipework Installation	
Act 9a	Cold Store Walls	Cold Store Walls	Composite Wall Cladding	
Act 10a	Syphonic Drainage	Syphonic Drainage	Pipework Installation	
Act 11a	Ground Floor	Ground Floor	In-situ Concrete Slab	Warehouse Ground Floor
Act 11b	Ground Floor	Upper Floor	In-situ Concrete Slab	Office Ground, First and Second Floors
Act 12a	Refrigeration	Refrigeration	Pipework Installation	
Act 13a	Dock Levellers	Dock Levellers	Dock Leveller Installation	Standard Docks
Act 14a	External Slab	External Slab	In-situ Concrete Slab	
Act 15a	Racking	Racking	Steel Racking Installation	
Act 16a	Internal Walls	Internal Walls	Composite Wall Panels	

4.1.2 FRAMEWORK INDICATORS

In order to determine the correct type and level of data needed to assess the initial embodied energy consumption of the project (including specific construction packages, activities and sub-contractors) 25 previous LCA studies were critically reviewed. This revealed various characteristics in terms of research scope, system boundaries, calculation methods, data sources, project types, and geographical locations. For example, Emmanuel (2004) and Rai et al. (2011) focused only on assessing material phase impacts, whereas Cole (1999) captured a wide range of data from material, transportation and construction phases. Impacts derived from the transportation of plant and equipment and operatives were commonly overlooked in the extant research.

Table 2 illustrates which project indicators were commonly acknowledged by practitioners as a form of required data (either captured or assumed) relative to different project life cycle phases. The indicators were organised in terms of project resources used across the three project life cycle phases. In order to increase the accuracy and granularity of results as well as tackle common assumptions within previous studies, all previously considered indicators were incorporated within the framework structure. Additions have also been included where the researchers felt this was appropriate (e.g. vehicle load capacity for plant and equipment transport).

Table 2 Comparison of project life cycle phases and associated embodied energy indicators acknowledged within previous LCA studies

	Project Life Cycle Phase[1]	MAT	TRAN						TRAN						TRAN						CON						
	Project Resource	Materials	Materials						Plant and Equipment						Operatives						Material, Plant and Equipment, and Operatives						
	Embodied Energy Indicators and Units[2]	a	b	c	d	e	f	g	b	c	d	e	f	g	b	c	d	e	f	g	c	c	c	h	d	e	i
Ref	Reference	Characteristics	Distance Travelled	Vehicle Used	Vehicle Fuel	Vehicle Fuel Type	Vehicle Load Capacity	Proportion of Load	Distance Travelled	Vehicle Used	Vehicle Fuel	Vehicle Fuel Type	Vehicle Load Capacity	Proportion of Load	Distance Travelled	Vehicle Used	Vehicle Fuel	Vehicle Fuel Type	Vehicle Load Capacity	Proportion of Load	Material Needed	Operatives Needed	Plant Needed	Plant Duration of Use	Plant Fuel Type	Plant Fuel Consumed	Plant Power Rating
1	Adalberth (1997)	✓	✓	✓																			✓				
2	Blengini and Di Carlo (2010)	✓	✓	✓																			✓				
3	Bribian et al. (2011)	✓	✓	✓			✓																				
4	Chang et al. (2012)	✓	✓	✓	✓	✓	✓																✓		✓	✓	✓
5	Chen et al. (2001)	✓	✓	✓																							
6	Cole (1999)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓				✓	✓	✓	✓	✓	
7	Cole and Kernan (1996)	✓																									
8	Emmanuel (2004)	✓																									
9	Fay et al. (2000)	✓																									
10	Fieldson and Rai (2009)	✓																					✓		✓		
11	Goggins et al. (2010)	✓	✓	✓	✓	✓	✓	✓																			
12	Gustavsson et al. (2010)	✓																							✓		
13	Halcrow Yolles (2010)	✓																									
14	Huberman and Pearlmutter (2008)	✓	✓	✓	✓																						
15	Kellenberger and Althaus (2009)	✓	✓	✓			✓	✓															✓				
16	Kofoworola and Gheewala (2009)	✓	✓	✓	✓				✓			✓											✓		✓	✓	
17	Leckner and Zmeureanu (2011)	✓	✓	✓			✓																				
18	Li et al. (2010)	✓	✓																				✓	✓	✓	✓	
19	Monahan and Powell (2011)	✓	✓												✓										✓	✓	
20	Pearlmutter et al. (2007)	✓	✓	✓	✓	✓																					
21	Rai et al. (2011)	✓																									
22	Scheuer at al. (2003)	✓	✓	✓																			✓	✓	✓	✓	
23	Smith et al. (1997)	✓	✓																								
24	Sodagar et al. (2008)	✓	✓	✓	✓	✓			✓	✓					✓	✓						✓	✓			✓	
25	Venkatarama Reddy and Jagadish (2003)	✓	✓		✓																						

[1] Project Life Cycle Phase: M, Material Phase.
[2] Embodied Energy Indicator Units: a (type, no., m^2, m^3, tonne); b (miles, km); c (type, no.); d (petrol, diesel, etc.); e (litres, kWh); f (tonne, m^3); g (%); h (hrs, days); i (v, a, watts).

4.1.3 FRAMEWORK STRUCTURE

The framework was designed to facilitate the capture and assessment of data via a three-tier structure. This structure helped to highlight the significance of each project life cycle phase and potential weaknesses within the data. The relationship between each project resource (i.e. material, plant and equipment, and operatives) and their impact relative to each project life cycle phase is shown in Figure 2.The diagram highlights the positioning and corresponding data connections (i.e. arrows) between one material, one item of plant and two operatives for an example construction activity. In relation to the construction phase, the structure assumes for each construction activity materials are assembled on-site via the use of plant and equipment by operatives. In terms of the transportation phase, the structure assumes the following for each construction activity: materials are transported once from their place of origin to the construction site; plant and equipment are transported to and from their place of origin and the construction site once; and operatives are transported to and from their place of origin and the construction site daily. Energy is consumed during the transportation of each project resource. In terms of the material phase, the structure assumes energy is consumed during the manufacture and production of materials which form the basis of each construction activity.

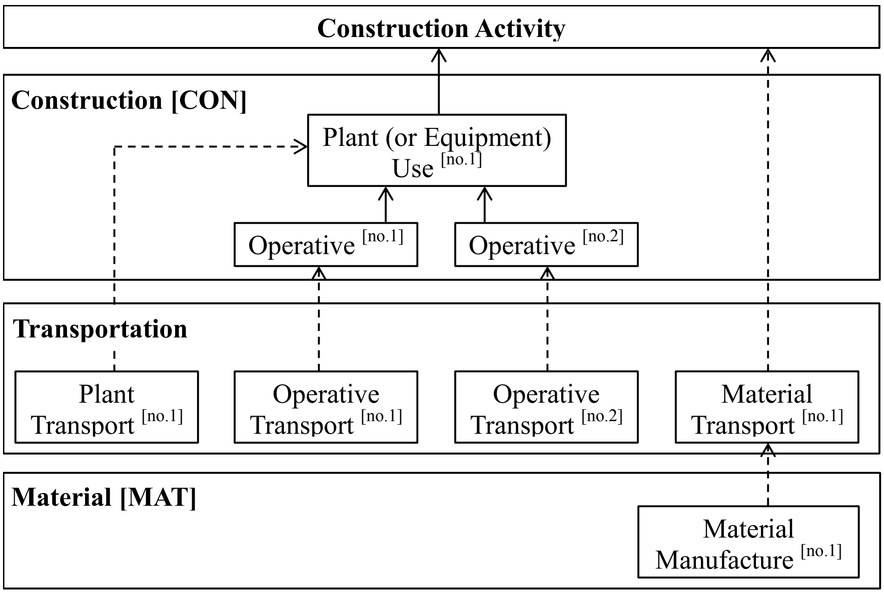

Figure 2 Framework structure for capturing project life cycle data for each project resource per construction activity (example)

4.1.4 FRAMEWORK EQUATIONS

Multiple equations were developed to assess the captured data and provide the link between the framework indicators and structure. The equations helped assign data to specific life cycle phases (material, transportation and construction), construction packages and construction activities to produce a holistic overview of the initial embodied energy level of the project. Each construction package was derived from an assorted number of construction activities. Typically, depending on contractual arrangements, sub-contractors were allocated responsibility for individual or all corresponding construction activities per construction package. Sub-contractors used multiple project resources (i.e. materials, plant and equipment, and operatives) to undertake each construction activity. The impact of these project resources was captured via assorted contractor current practices and assigned per construction activity for each construction package; resulting in the impact of each life cycle phase. Hence, the total material embodied impact was calculated as follows:

$$EE_{MAT} = \sum_{i=1}^{n}(M_i m_i) \quad (1)$$

where EE_{MAT} equals the total material embodied energy (MJ) of the project, n represents the total number of materials used, M_i represents the volume of material i (m^3), and m_i represents the energy used per volume of material i (MJ/m^3). The total transportation embodied impact was calculated as follows:

$$EE_{TRAN} = \sum_{i=1}^{n} EE_{TRAN,Mat,i} + \sum_{j=1}^{m} EE_{TRAN,Ops,j} + \sum_{k=1}^{o} EE_{TRAN,Plant,k} \quad (2)$$

where EE_{TRAN} equals the total transportation embodied energy (MJ) of the project, n represents the total number of materials transported, $EE_{TRAN,Mat,i}$ represents the energy used in the transport of material i (MJ), m represents the total number of operatives transported, $EE_{TRAN,Ops,j}$ represents the energy used in the transport of operative j (MJ), o represents the total number of plant (or equipment) items transported, $EE_{TRAN,Plant,k}$ represents the energy used in the transport of plant (or equipment) item k (MJ). The total construction embodied impact was calculated as follows:

$$EE_{CON} = \sum_{l=1}^{p} EE_{Fuel,l} \quad (3)$$

where EE_{CON} equals the total construction embodied energy (MJ) of the project, p represents the total number of plant (or equipment) items which consume energy on-site, EE_{Fuel} represents the energy consumed during the construction process by plant (or equipment) item l (MJ). Therefore, the total initial embodied energy impact was calculated as follows:

$$EE_{Initial} = EE_{MAT} + EE_{TRAN} + EE_{CON} \quad (4)$$

where $EE_{Initial}$ equals the total initial embodied energy (MJ) of the project.

4.1.5 FRAMEWORK ALIGNMENT

Throughout the construction phase the contractor maintained a series of practices intended to aid their management of the project. These practices captured assorted project data during different intervals. The typical characteristics of these practices in terms of project resource consideration (i.e. material, plant and equipment, and operative data) are outlined within Table 3. The captured data per practice was reviewed in order to determine which practice could provide information to support specific embodied energy indicators affiliated to each project resource across different life cycle phases. Thus, the alignment of current practices with embodied indicators per project life cycle phase is illustrated within Table 4.

Table 3 Information characteristics of the contractor's current practices

Current Practice	Information Characteristics[3]
Bill of Quantities (BoQ)[1]	Information on MAT type and quantity per sub-contractor
Design Drawings[1]	Information on MAT specification, detail and measurement per sub-contractor
Resource Database[1]	Information (e.g. daily, weekly or monthly) on MAT, P&E, OPP values per sub-contractor
Plant Register[1]	Information on P&E type and quantity per sub-contractor
On-site Energy Management Procedure[1]	Information (e.g. monthly) on fuel type and quantity per sub-contractor
Sign-in Sheets[1]	Information (e.g. daily, weekly or monthly) on OPP values per sub-contractor
	Information (e.g. daily, weekly or monthly) on transportation type, distance travelled, and fuel type for MAT, P&E, OPP movements per sub-contractor
Programme of Works (PoW)[2]	Information (e.g. daily, weekly or monthly) on construction package and activity duration
Site Waste Management Plan (SWMP)[1]	Information (e.g. daily, weekly or monthly) on MAT waste consumption per sub-contractor
	Information (e.g. daily, weekly or monthly) on transportation type, distance travelled, and fuel type for MAT waste per sub-contractor

[1] Information captured relative to sub-contractor.
[2] Information captured relative to construction package and construction activity.
[3] Provides information regarding: MAT, Material values; P&E, Plant and Equipment values; OPP, Operative values.

4.2 QUANTITATIVE ANALYSIS

Quantitative data was captured through non-intrusive participant observation. The lead researcher was based on the construction site throughout the entire construction phase of 30 weeks. It was felt that this method would produce a detailed account of primary data derived from the contractor's actions and practices needed for an initial embodied energy assessment (in line with Bryman, 1988; Stewart, 1998). This approach was also undertaken in order to limit the need for secondary source data derived from post-construction contractor queries; which as a data source, could lead to possible uncertainty in results. All project information and data was organised and analysed via multiple Microsoft Excel spreadsheets. This simple data management approach was adopted due to its compatibility with the contractor's practices.

In order to conform to previous studies and improve the comparability of results, both embodied energy and carbon was considered during the analysis; especially as these terms are interlinked within previous research (Dakwale et al., 2011; Dixit et al., 2012). Embodied energy is commonly measured in terms of MJ (106) or GJ (109) and embodied carbon in terms of kilograms of carbon dioxide equivalent (kgCO2e) whereby the term 'e' is used to normalise each greenhouse gas (GHG) relative to the impact of one unit of carbon dioxide (CO2) (BSRIA, 2011). Thus, in relation to the framework equations (4-7), embodied energy (EE) would be replaced with embodied carbon (EC).

4.2.1 MATERIAL DATA

Each construction package consisted of smaller construction activities which included numerous materials. Similar to previous studies, the embodied impact (energy and carbon) of these materials was assessed via the ICE material database (Goggins et al., 2010; Rai et al., 2011). This data was correlated against the material characteristics such as material area (m2), volume (m3), and thickness (m) addressed within the contractor's BoQ's and design drawings (Scheuer et al., 2003; Kofoworola and Gheewala, 2009; Chang et al., 2012) to obtain the total embodied energy and carbon levels for each construction package.

Table 4 Alignment of current practices with embodied energy indicators per project life cycle

Life Cycle Phase	Project Resources	Embodied Energy Indicators	Units	Current Practices[1]
Material	Material	Characteristics	type, no., m2, m3, tonne	BoQ, Drawings
Transportation	Material	Distance travelled	miles, km	Sign-in sheet, SWMP
		Vehicle used	type, no.	Sign-in sheet, SWMP
		Vehicle fuel used	petrol, diesel etc.	Sign-in sheet, SWMP
		Vehicle fuel consumption	litres, kWh	Sign-in sheet, SWMP
		Vehicle load capacity	tonne, m^3	Sign-in sheet, SWMP
		Proportion of load	%	Sign-in sheet, SWMP
	Plant and Equipment	Distance travelled	miles, km	Sign-in sheet, SWMP
		Vehicle used	type, no.	Sign-in sheet, SWMP
		Vehicle fuel used	petrol, diesel etc.	Sign-in sheet, SWMP
		Vehicle fuel consumption	litres, kWh	Sign-in sheet, SWMP
		Vehicle load capacity	tonne, m^3	Sign-in sheet, SWMP
		Proportion of load	%	Sign-in sheet, SWMP
	Operatives	Distance travelled	miles, km	Sign-in sheet
		Vehicle used	type, no.	Sign-in sheet
		Vehicle fuel used	petrol, diesel etc.	Sign-in sheet
		Vehicle fuel consumption	litres, kWh	Sign-in sheet
		Vehicle load capacity	tonne, m^3	Sign-in sheet
		Proportion of load	%	Sign-in sheet
Construction	Material + Plant and Equipment + Operatives	Material needed	type, no.	Resource, BoQ, PoW
		Operatives needed	type, no.	Resource, PoW
		Plant needed	type, no.	Plant register, PoW
		Plant duration of use	hrs, days	Plant register, PoW
		Plant fuel type	petrol, diesel etc.	Plant register, Energy Procedure
		Plant fuel consumed	litres, kWh	Plant register, Energy Procedure
		Plant power rating	v, a, watts	Plant register

[1] Contractors current practices (i.e. data sources): PoW, Programme of Works; BoQ, Bill of Quantities; Resource, Resource Database; Energy Procedure, On-site Energy Management Procedure; SWMP, Site Waste Management Plan.

4.2.2 TRANSPORTATION DATA

It was expected the embodied impact of the transportation phase would be calculated by applying values such as distance travelled and vehicle type from the contractor practices to the conversion factors addressed within the 2012 Guidelines to Defra/ DECC's GHG Conversion Factors for Company Reporting document (Defra Guide) (Defra, 2012). However, due to inadequacies within certain practices (i.e. sign-in sheets) members of the project team were required to verbally confirm this data.

4.2.3 CONSTRUCTION DATA

Data was primarily captured from the contractor's existing on-site energy management procedure which enabled fuel type and quantities to be captured from sub-contractors during the construction phase on a monthly basis. Similar to the transportation phase, the embodied impact of the construction phase was calculated by applying values captured within the existing on-site energy management procedure to the conversion factors addressed within the Defra Guide (Defra, 2012).

5 RESULTS AND DISCUSSION

5.1 QUANTITATIVE ANALYSIS

Quantitative analysis explored the practical capabilities of the framework via the collection and assessment of data derived from the contractor’s current practices. Data which reflected the energy consumption during the material, transportation and construction phases of a UK non-domestic sector project was captured and analysed.

5.1.1 MATERIAL DATA

Table 5 illustrates the data type, data source and calculation methods used to assess the material impacts relative to individual construction activities. The table content is based upon the method documented within the ICE material database. Notably the evidence highlighted diversity between embodied energy and carbon levels across the construction packages. In terms of embodied impacts, the most significant construction packages were the ground and upper floors, external slab and frame construction packages; reflecting similar results to Halcrow Yolles (2010). In relation to embodied energy the construction packages were responsible for 46.4%, 18.7% and 13.5% of the total. In relation to embodied carbon the construction packages were responsible for 19.4%, 64.1% and 6.5% respectively. The slight change in ranking was due to the change in coefficient values for the respective materials (i.e. concrete). Predominately the concrete used within the ground and upper floors package consisted of steel fibre-reinforcement which was deemed more energy intensive (7.8 MJ/kg) to produce compared to traditional in-situ concrete with steel reinforcement bars (2.1 MJ/kg) used for the external slab package. However, as noted by BSRIA (2011), there is a high degree of uncertainty surrounding the coefficient value for the steel fibre-reinforcement form of concrete within the ICE material database. Nonetheless, similar to Scheuer et al. (2003), the results highlight the significance of steel and concrete-based materials due to their corresponding volume and mass as opposed to their environmental impact during manufacture. Overall, in terms of project life cycle energy, the material phase was responsible for total embodied energy and carbon levels of 123,539.2 GJ and 17,429,524.0 kgCO2e respectively. Impacts per sub-contractor are displayed within Table 6 and 7.

Table 5 Material life cycle impacts (embodied energy and carbon) and calculation methods per construction activity

Data Source[a]	ICE	BoQ		BoQ	BoQ			ICE	ICE					BoQ		
Calculation Method			A x B		B x D	C x D	A x E			C x H	C x J	F x H (or G x H)[e]	G x J		M / P	N / P
Calculation Ref.	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R
Calc' Units[b c]	1	2	3	4	5	6	6	7	8	9	10	11	12	4	9	10
Act Ref. [d]	Density	Thickness	Mass	Area	Volume	Total Mass [Area]	Total Mass [Vol]	EE per Mass	EC per Mass	EE per 1m^2	EC per 1m^2	EE for Whole Build	EC for Whole Build	Total Build Area	EE per 1m^2 [Whole]	EC per 1m^2 [Whole]
Act 1a	2,240.0	0.6	1,366.4	19,564.0	11,934.0	2.67(x10^7)	-	0.1	0.0	68.3	6.8	1.34(x10^6)	1.34(x10^5)	19,564.0	68.3	6.8
Act 1b	2,240.0	0.3	739.2	19,564.0	6,456.1	1.45(x10^7)	-	0.1	0.0	37.0	3.7	7.23(x10^5)	7.23(x10^4)	19,564.0	37.0	3.7
Act 1c	1,460.0	0.3	481.8	2,349.0	775.2	1.13(x10^6)	-	0.5	0.0	216.8	11.1	5.09(x10^5)	2.60(x10^4)	19,564.0	26.0	1.3
Act 2a	2,240.0	-	-	-	518.4	-	1.16(x10^6)	0.1	0.0	-	-	5.81(x10^4) [e]	5.81(x10^3)	19,564.0	3.0	0.3
Act 3a	1,900.0	0.1	237.5	191.8	24.0	4.55(x10^4)	-	0.5	0.1	123.5	16.4	2.37(x10^4)	3.14(x10^3)	19,564.0	1.2	0.2
Act 3b	1,900.0	0.4	741.0	120.8	47.1	8.95(x10^4)	-	0.5	0.1	385.3	51.1	4.65(x10^4)	6.18(x10^3)	19,564.0	2.4	0.3
Act 3c	45.0	-	-	-	4.4	-	1.99(x10^2)	84.4	2.0	-	-	1.68(x10^4) [e]	3.97(x10^2)	19,564.0	0.9	0.0
Act 3d	2,300.0	-	-	-	2.8	-	6.51(x10^3)	1.3	0.2	-	-	8.20(x10^3) [e]	1.04(x10^3)	19,564.0	0.4	0.1
Act 3e	7,800.0	-	-	-	3.3	-	2.58(x10^4)	28.7	2.0	-	-	7.39(x10^5) [e]	5.03(x10^4)	19,564.0	37.8	2.6
Act 3f	2,400.0	-	-	-	425.0	-	1.02(x10^6)	1.8	0.2	-	-	1.83(x10^6) [e]	1.82(x10^5)	19,564.0	93.5	9.3
Act 4a	7,800.0	-	-	-	38.0	-	2.96(x10^5)	28.7	2.0	-	-	8.50(x10^6) [e]	5.78(x10^5)	19,564.0	434.5	29.6
Act 4b	7,800.0	-	-	-	36.5	-	2.85(x10^5)	28.7	2.0	-	-	8.17(x10^6) [e]	5.55(x10^5)	19,564.0	417.4	28.4
Act 5a	7,800.0	-	-	-	5.4	-	4.20(x10^4)	36.0	2.8	-	-	1.51(x10^6) [e]	1.19(x10^5)	19,564.0	77.4	6.1
Act 5b	140.0	-	-	-	11.2	-	1.57(x10^3)	16.6	1.2	-	-	2.61(x10^4) [e]	1.89(x10^3)	19,564.0	1.3	0.1
Act 5c	7,800.0	-	-	-	1.6	-	1.22(x10^4)	34.4	2.7	-	-	4.19(x10^5) [e]	3.29(x10^4)	19,564.0	21.4	1.7
Act 5d	8,600.0	-	-	-	0.2	-	1.55(x10^3)	40.0	2.2	-	-	6.19(x10^4) [e]	3.39(x10^3)	19,564.0	3.2	0.2
Act 5e	8,600.0	-	-	-	0.2	-	1.38(x10^3)	40.0	2.2	-	-	5.50(x10^4) [e]	3.01(x10^3)	19,564.0	2.8	0.2
Act 6a	46.0	0.2	9.7	7,523.1	1,579.9	7.27(x10^4)	-	28.0	1.4	270.5	13.0	2.03(x10^6)	9.81(x10^4)	19,564.0	104.0	5.0
Act 6b	46.0	0.2	9.7	19,564.0	4,108.4	1.89(x10^5)	-	28.0	1.4	270.5	13.0	5.29(x10^6)	2.55(x10^5)	19,564.0	270.5	13.0
Act 7a	2,000.0	0.2	400.0	66.5	13.3	2.66(x10^4)	-	1.5	0.2	584.0	78.9	3.88(x10^4)	5.25(x10^3)	19,564.0	2.0	0.3
Act 7b	2,000.0	0.2	400.0	704.0	140.8	2.82(x10^5)	-	1.5	0.2	584.0	78.9	4.11(x10^5)	5.55(x10^4)	19,564.0	21.0	2.8
Act 8a	7,870.0	-	-	-	6.5	-	5.11(x10^4)	25.0	1.9	-	-	1.28(x10^6) [e]	9.76(x10^4)	19,564.0	65.3	5.0
Act 9a	30.0	0.2	4.5	8,051.0	1,207.7	3.62(x10^4)	-	101.5	4.3	456.8	19.2	3.68(x10^6)	1.54(x10^5)	19,564.0	188.0	7.9
Act 10a	45.0	-	-	-	3.2	-	1.44(x10^2)	84.4	2.0	-	-	1.22(x10^4) [e]	2.88(x10^2)	19,564.0	0.6	0.0
Act 11a	2,500.0	0.2	375.0	19,564.0	2,934.6	7.34(x10^6)	-	7.8	0.5	2,906.3	168.8	5.69(x10^7)	3.30(x10^6)	19,564.0	2,906.3	168.8
Act 11b	2,400.0	0.2	360.0	1,467.0	220.1	5.28(x10^5)	-	1.0	0.2	349.2	54.7	5.12(x10^5)	8.03(x10^4)	19,564.0	26.2	4.1
Act 12a	8,600.0	-	-	-	0.1	-	9.46(x10^2)	40.0	2.2	-	-	3.78(x10^4) [e]	2.07(x10^3)	19,564.0	1.9	0.1
Act 13a	7,800.0	-	-	-	3.8	-	2.93(x10^4)	21.5	1.5	-	-	6.31(x10^5) [e]	4.49(x10^4)	19,564.0	32.2	2.3
Act 14a	2,400.0	0.2	480.0	23,409.0	4,681.8	1.12(x10^7)	-	2.1	1.0	985.9	477.5	2.31(x10^7)	1.12(x10^7)	19,564.0	1,179.7	571.3
Act 15a	7,800.0	-	-	-	24.5	-	1.91(x10^5)	28.7	2.0	-	-	5.49(x10^6) [e]	3.73(x10^5)	19,564.0	280.5	19.1
Act 16a	140.0	0.1	14.0	669.5	67.0	9.37(x10^3)	-	16.8	1.1	235.2	14.7	1.57(x10^5)	9.84(x10^3)	19,564.0	8.0	0.5

[a] Data Source; ICE, ICE material database (external literature); BoQ, Bill of Quantities and Design Drawings (contractor current practices).
[b] Calculation Units; 1 (kg/m^3); 2 (m); 3 (kg/m^2); 4 (m^2); 5 (m^3); 6 (kg); 7 (MJ/kg); 8 (kgCO_2e/kg); 9 (MJ/m^2); 10 (kgCO_2e/m^2); 11 (MJ); 12 (kgCO_2e).
[c] EE, Embodied Energy; EC, Embodied Carbon.
[d] Activity Reference keyed to Table 1 contents.
[e] Calculation Method; G x H (Total Mass [Vol] x EE per Mass).

5.1.2 TRANSPORTATION DATA

Only data derived from the contractor's plant and equipment movements were captured, as opposed to material, plant and equipment, and operative movements across all construction activities. This was due to multiple challenges contained within the contractor's current practices, which are addressed within the following section. Data collection was focused on specific items of plant and equipment; site cabins, fuel deliveries and waste skip movements. The 16 site cabins were transported a distance of 119 km to site via articulated lorries (diesel fuelled). The 22 fuel deliveries were transported a distance of 51 km to site via rigid lorries (diesel fuelled). In terms of the waste skip movements, distance travelled and vehicle used data was displayed within the Site Waste Management Plan (SWMP). This revealed 919 skip movements, travelling a distance of 19 km to site via rigid lorries (diesel fuelled). Interestingly, the distance travelled to site for skip movements was similar to the assumed value (i.e. 20 km) previously used by Adalberth (1997). Overall, despite limited transportation data being captured, in terms of project life cycle energy, the transportation phase was responsible for total embodied energy and carbon levels of 517.6 GJ and 35,281.7 kgCO2e respectively. Impacts per sub-contractor are displayed within Table 6 and 7.

Table 6 Total embodied energy level of each sub-contractor per life cycle phase

Sub-contractor	Embodied Energy (GJ)[1]					
	MAT[2]	TRAN[2]			CON[2]	Total EE across all life cycle phases
		Material	P&E[3]	Operatives		
Main Contractor	-	-	517.6 (100%)	-	497.3 (34.5%)	1,014.9 (0.8%)
Earthworks	2,569.0 (2.1%)	-	-	-	148.1 (10.3%)	2,717.1 (2.2%)
Foundations	58.1 (0.0%)	-	-	-	8.2 (0.6%)	66.3 (0.1%)
Groundworks	2,663.9 (2.2)	-	-	-	634.1 (44.0%)	3,298.1 (2.6%)
Frame	16,666.8 (13.5%)	-	-	-	44.1 (3.1%)	16,711.0 (13.3%)
M&E	2,075.2 (1.7%)	-	-	-	5.6 (0.4%)	2,080.8 (1.7%)
External Walls	7,326.5 (5.9%)	-	-	-	37.0 (2.6%)	7,363.6 (5.9%)
Retaining Walls	450.0 (0.4%)	-	-	-	5.3 (0.4%)	455.3 (0.4%)
Sprinklers	1,276.9 (1.0)	-	-	-	14.2 (1.0%)	1,291.1 (1.0%)
Cold Store Walls	3,677.3 (3.0%)	-	-	-	2.3 (0.2%)	3,679.6 (2.9%)
Syphonic Drainage	12.2 (0.0%)	-	-	-	4.4 (0.3%)	16.5 (0.0%)
Ground Floor	57,370.2 (46.4%)	-	-	-	18.8 (1.3%)	57,389.0 (45.7%)
Refrigeration	37.8 (0.0%)	-	-	-	10.7 (0.7%)	48.5 (0.0%)
Dock Levellers	630.6 (0.5%)	-	-	-	3.3 (0.2%)	633.9 (0.5%)
External Slab	23,079.4 (18.7%)	-	-	-	0.6 (0.0%)	23,080.0 (18.4%)
Racking	5,487.8 (4.4%)	-	-	-	4.5 (0.3%)	5,492.3 (4.4%)
Internal Walls	157.5 (0.1%)	-	-	-	1.2 (0.1%)	158.7 (0.1%)
Total EE per life cycle[2]	123,539.20 (100%)	-	517.6 (100%)	-	1,439.7 (100%)	
Total EE all life cycle[4]						125,496.7 (100%)

[1] Project life cycle phase: MAT, Material; TRAN, Transport; CON, Construction.
[2] Total embodied energy level (%) of each sub-contractor per life cycle phase.
[3] P&E, Plant and Equipment.
[4] Total embodied energy level (%) of each sub-contractor across all life cycle phases.

5.1.3 CONSTRUCTION DATA

Data captured from the contractor’s existing on-site energy management procedure is displayed in Table 8. The 130,775 litres of red diesel and 1,606 litres of petrol delivered and consumed by the contractor and sub-contractors represented 98.8% and 1.2% of the total embodied impacts respectively. The three most significant packages were the groundworks, project management (i.e. the contractor), and earthworks, which were responsible for 44.0%, 34.5% and 10.3% of the total embodied impacts respectively. The groundworks package took 28 weeks (136 business days) to complete and primarily consisted of the installation of drainage systems, pile caps and kerbs and edging. Activities which formed the basis of this package were physical and labour-intensive; hence the package was responsible for the most operative man days (4,235 days) and fuel consumption (both red diesel and petrol). This positive relationship between operative numbers and fuel consumption is not reflected in the earthworks construction package, as 13,614 litres of red diesel was consumed during only 188 operative man days. Each operative was responsible for approximately 72 litres of red diesel consumption per day as opposed to 14 litres for the groundworks package.

Table 7 Total embodied carbon level of each sub-contractor per life cycle phase

Sub-contractor	Embodied Carbon ($kgCO_2e$)[1]					
	MAT[2]	TRAN[2]			CON[2]	Total EC across all life cycle phases
		Material	P&E[3]	Operatives		
Main Contractor	-	-	35,281.7 (100%)	-	138,152.0 (34.5%)	173,433.7 (1.0%)
Earthworks	232,000.0 (1.3%)	-	-	-	41,132.0 (10.3%)	273,132.0 (1.5%)
Foundations	5,806.1 (0.0%)	-	-	-	2,275.0 (0.6%)	8,081.1 (0.0%)
Groundworks	243,285.3 (1.4%)	-	-	-	176,144.3 (44.0%)	419,429.6 (2.3%)
Frame	1,133,601.3 (6.5%)	-	-	-	12,262.5 (3.1%)	1,145,863.8 (6.4%)
M&E	160,124.3 (0.9%)	-	-	-	1,566.9 (0.4%)	161,691.3 (0.9%)
External Walls	353,243.3 (2.0%)	-	-	-	10,284.5 (2.6%)	363,527.8 (2.0%)
Retaining Walls	60,777.0 (0.3%)	-	-	-	1,468.4 (0.4%0	62,245.4 (0.3%)
Sprinklers	97,555.7 (0.6%)	-	-	-	3,940.3 (1.0%)	101,496.1 (0.6%)
Cold Store Walls	154,337.7 (0.9%)	-	-	-	634.5 (0.2%)	154,972.1 (0.9%)
Syphonic Drainage	288.0 (0.0%)	-	-	-	1,219.4 (0.3%)	1,507.4 (0.0%)
Ground Floor	3,381,699.2 (19.4%)	-	-	-	5,222.8 (1.3%)	3,386,922.1 (19.0%)
Refrigeration	2,071.7 (0.0%)	-	-	-	2,969.9 (0.7%)	5,041.7 (0.0%)
Dock Levellers	44,871.8 (0.3%)	-	-	-	921.5 (0.2%)	45,793.3 (0.3%)
External Slab	11,176,767.5 (64.1%)	-	-	-	161.7 (0.0%)	11,176,929.2 (62.6%)
Racking	373,253.4 (2.1%)	-	-	-	1,256.9 (0.3%)	374,510.3 (2.1%)
Internal Walls	9,841.7 (0.1%)	-	-	-	332.3 (0.1%)	10,174.0 (0.1%)
Total EC per life cycle[2]	17,429,524.0 (100%)	-	35,281.7 (100%)	-	399,944.9 (100%)	
Total EC all life cycle[4]						17,864,750.9 (100%)

[1] Project life cycle phase: MAT, Material; TRAN, Transport; CON, Construction.
[2] Total embodied carbon level (%) of each sub-contractor per life cycle phase.
[3] P&E, Plant and Equipment.
[4] Total embodied carbon level (%) of each sub-contractor across all life cycle phases.

The contractor's red diesel consumption was due to the operation and maintenance of 16 site cabins, which were used by contractor and sub-contractor staff. In this instance, the contractor supplied and paid for the sub-contractor's red diesel consumption. These site cabins consisted of kitchen and wash facilities, changing and drying rooms in addition to multiple meeting and office areas. In terms of project life cycle energy the construction phase was responsible for total embodied energy and carbon levels of 1,439.7 GJ and 399,945 kgCO2e respectively. Impacts per sub-contractor are displayed within Table 6 and 7.

Table 8 Basic project information per sub-contractor during the construction phase

Sub-contractor	Duration[1]	Operative Man Days	Red Diesel Consumption[2]	Petrol Consumption[2]
Main Contractor	146	1,372	45,726	0
Earthworks	25	188	13,614	0
Foundations	136	37	753	0
Groundworks	25	4,235	57,811	660
Frame	55	677	3,957	137
M&E	44	983	460	79
External Walls	105	947	3,404	0
Retaining Walls	95	139	486	0
Sprinklers	80	550	896	0
Cold Store Walls	45	176	210	0
Syphonic Drainage	37	34	365	52
Ground Floor	20	158	1,247	649
Refrigeration	20	888	983	0
Dock Levellers	30	124	305	0
External Slab	19	103	32	29
Racking	16	109	416	0
Internal Walls	70	76	110	0
Totals	968	10,796	130,775	1,606

[1] Duration, business days (5 days per week).
[2] Fuel Consumption, litres.

5.1.4 KEY FINDINGS AND ASSUMPTIONS

In terms of overall project life cycle energy, the material phase was responsible the largest embodied impacts (energy and carbon) (Table 9). The results emphasised the importance of steel and concrete-based materials as the ground and upper floor, external slab and frame were the most significant construction packages in terms of embodied energy and carbon. In terms of embodied carbon, only the syphonic drainage and refrigeration construction packages contained larger construction phase impacts than material phase impacts.

Table 9 Total embodied energy and carbon results per life cycle phase

Life Cycle Phase	Embodied Energy (GJ)	Ratio (%)	Embodied Carbon (kgCO2e)	Ratio (%)
Material [MAT]	123,539.0	98.4	17,429,524.1	97.6
Transportation [TRAN]	517.6	0.4	35,281.7	0.2
Construction [CON]	1,439.8	1.2	399,944.9	2.2
Total	**125,496.4**	**100**	**17,864,750.7**	**100**

Due to limitations associated with the data sources and the complex nature of the construction project, certain working assumptions were necessary. It was assumed that only 80% of the total material scope within the groundworks, electrical, mechanical and refrigeration construction packages was captured due to the following limitations: the selection of materials included in the ICE material database; measurement and specification disparity within design drawings and BoQ's; and time constraints for managing data. Consequently, it is highly probable that the material impacts for the specified construction packages and the overall project would be higher than reported. Regarding the use of the Defra Guide (Defra, 2012), because embodied energy levels relative to fuel usage (i.e. diesel, red diesel, petrol) is not included, these values were derived from embodied carbon values for transportation and on-site construction life cycle impacts (Table 10).

Table 10 Embodied energy and carbon conversion factors for fuel use during transportation and construction life cycle phases

Eq.	Fuel Type	A[1]	Units		A[1]	Units[2]	Notes	Reference	Life Cycle Phase
(a)	Diesel	1	litre	=	2.5835	$kgCO_2e$	Average biofuel blend	Defra (2012) Table 1b	TRAN
(b)	Red Diesel	1	litre	=	3.0213	$kgCO_2e$	Gas oil	Defra (2012) Table 1b	CON
(c)	Petrol	1	litre	=	2.2423	$kgCO_2e$	Average biofuel blend	Defra (2012) Table 1b	CON
(d)	Diesel	1	kWh	=	0.2454	$kgCO_2e$	Average biofuel blend	Defra (2012) Table 1c	TRAN
(e)	Red Diesel	1	kWh	=	0.2778	$kgCO_2e$	Gas oil	Defra (2012) Table 1c	CON
(f)	Petrol	1	kWh	=	0.2357	$kgCO_2e$	Average biofuel blend	Defra (2012) Table 1c	CON
(g)	Diesel	1	km	=	0.8336	$kgCO_2e$	Rigid HGV (UK mean)	Defra (2012) Table 7d	TRAN
(h)	Diesel	1	km	=	0.9983	$kgCO_2e$	Artic HGV (UK mean)	Defra (2012) Table 7d	TRAN
(x)	Red Diesel	1	litre	=	10.8770	kWh	Gas oil	Derived from (b) & (e)	CON
(y)	Petrol	1	litre	=	9.3180	kWh	Average biofuel blend	Derived from (c) & (f)	CON

[1] A, Amount.
[2] Units, $kgCO_2e$ total direct GHG.

5.2 CHALLENGES FOR INITIAL EMBODIED ENERGY ASSESSMENT

Multiple challenges embedded within the contractor's current practices were revealed as a consequence of the research. These relate to the programme of works; plant register; on-site energy management procedure; sign-in sheets; resource database; and various forms of environmental reporting.

5.2.1 PROGRAMME OF WORKS

The programme of works (PoW) is a tool commonly used by contractor's to help organise and coordinate project resources and the sequential development of a project from initiation to practical completion (Meikle and Hillebrandt, 1988). The PoW developed by the contractor was regarded as the target programme and was used by all project stakeholders (i.e. client, contractor, sub-contractors) to review progression and help plan resources for future on-site activities. However, the there was no correlation between this particular PoW and the sequence of sub-contractor activities. Thus the resident researcher had to ask the contractor for confirmation of this information, which was forthcoming. It was discovered the contractor developed multiple individual phasing and logistical plans for critical packages and the sub-contractors created unique programmes which highlighted approximate construction resources per construction activity. There was no consistency between the various forms of programmes used, activity ownership, duration or terminology.

5.2.2 PLANT REGISTER

The Provision and Use of Work Equipment Regulations 1998 (PUWER) has set the current standard for inspecting, documenting and maintaining the operational performance of plant and equipment within the construction industry (HSE, 2009). In order to satisfy the requirements of the regulation the contractor captured relevant information (i.e. plant description, serial number, and date of next inspection) from each sub-contractor when new items of plant and equipment arrived and were utilised on-site. This information was recorded on the plant register, which was a collection of multiple sub-contractor specific registers as opposed to a single source of information. Perhaps, unsurprisingly, the information relating to sub-contractors plant and equipment varied significantly in terms of content, detail, legibility and clarity; with no consistent terminology used to describe similar or even identical items of plant. Despite the information being reviewed periodically by the contractor the level and type of information received was not organised or processed beyond the original format. As a result there appears to be no correlation between the items of plant and equipment and specific construction packages or activities.

5.2.3 ON-SITE ENERGY MANAGEMENT

Throughout the project the contractor's on-site energy management procedure was used to record the total project fuel consumption (i.e. red diesel, petrol) on a monthly basis. The contractor's fuel consumption was reviewed against hard copies of fuel delivery receipts; maintained by the contractor for commercial and auditing purposes. The same level of verification was not mirrored for the sub-contractor data because sub-contractors were not required to provide fuel delivery receipts. Consequently there is ambiguity in terms of when the fuel was delivered, the quantity delivered and how much fuel was originally on-site. Typically bowsers and large items of plant used during construction are full of fuel (red diesel) when initially delivered to site, though this quantity of fuel was not captured by the contractor's reporting procedure. Thus the overall construction phase impacts would be greater than the actual reported values. The fuel data was not pro-rata or measured at smaller intervals (weeks, days etc.) by the contractor or sub-contractors. Thus from the data alone, there appears to be no clear understanding as to how, where and why fuel is being consumed during specific construction activities beyond monthly intervals.

5.2.4 SIGN-IN SHEETS AND RESOURCE DATABASE

There were two versions of sign-in sheets used throughout the project duration. Despite both versions containing the same name 'Contractors sign-in sheet' these were different in terms of content, use and location within the contractor's on-site cabins. One version of the sign-in sheet was located adjacent to the ground floor site cabins entrance, which was designated as a sub-contractor communal area. This version was used as the sub-contractor sign-in sheet. Each operative was required to provide the following information: induction number, date, name, signature, company name, time in, and time out. Throughout the project duration the sign-in sheet was thoroughly filled in by the operatives. It could be argued that the success of this sign-in sheet was due to the contractor using the sheets as a way to review sub-contractor payments relative to man days.

There were occasions when sub-contractors maintained their own form of sign-in sheet; hence this information was not captured on the contractor's equivalent sign-in sheet. In order to ensure the contractor was fully aware of on-site operative numbers, sub-contractor management passed this information weekly to the contractor's administrator, who extracted the relevant information and incorporated it within the contractor's Resource Database. This Microsoft Access database was designed to support the collection and assessment of project data in terms of resources such as the operative, plant, equipment, and materials. The information from the sub-contractors sign-in sheet was also stored in this database, though the database was not fully maintained and only the contractor's administrator had sufficient knowledge of the database. It was discovered there was no mandatory requirement for the contractor team to use the database; it was simply perceived as a useful tool which could help certain reporting requirements.

An additional sign-in sheet was located adjacent to the entrance of the first floor site cabins, which was designated as a contractor communal area. Primarily, this sign-in sheet was used as the visitor's sign-in sheet. Each site visitor was required to provide the following information: date, name, company, signature, time-in/out, transport type, fuel type, distance travelled, and onward travel distance. Visitors provided information such as date, name, company, and signature, but largely failed to provide the information related to transport type, fuel type, distance travelled, and onward travel distance (which was voluntary).

5.2.5 ENVIRONMENTAL REPORTING

Collectively all previous current practices were used by the contractor to help fulfil their project environment compliance under BREEAM. The project was certified under the BREEAM Industrial 2008 criteria. In particular, the contractor targeted 4 credits related to the criterion 'Management 3 – Construction Site Impacts' (BRE, 2008), which was based upon managing the construction site in an environmentally efficient manner with regards to resource use, energy consumption and pollution. Interestingly the criterion supports initial embodied energy consideration as both transportation and construction impacts were expected to be monitored, reported and performance targets set during the construction phase. Construction impacts were recorded via the on-site energy management procedure. However, due to multiple sign-in sheet challenges transportation impacts were not monitored throughout the entire construction phase, hence this aspect of the criterion this was not achieved. Evidently, there was no awareness demonstrated amongst the contractor operatives regarding the importance of the on-site energy management procedure and sign-in sheets towards completing this criterion. Moreover, three additional criterions considered impacts derived from the material phase; 'Material 1 – Materials Specification (Major Building Elements)', 'Material 2 – Hard Landscaping and Boundary Protection', and 'Material 6 – Insulation' (BRE, 2008). Notably 5 out of 6 credits were achieved due to the client and contractor commitment towards the use of materials with low embodied impact.

The SWMP, which demonstrated the project total waste consumption during the construction phase, was managed by the contractor's construction manager. Information such as distance travelled, load capacity and form of transportation type was all recorded on the SWMP and updated infrequently by the construction manager. The contractor initially employed the use of segregated skips (e.g. timber, metal, plastic, cardboard) for all sub-contractors to use, though this method was not maintained during the final stages of the construction phase (i.e. during the labour-intensive fit out period). Despite the reason not being investigated, it seems likely if segregated skips were maintained material waste and associated transportation impacts relative to specific construction packages, activities and sub-contractors could have been calculated to increase the granularity of the results.

6 CONCLUSION

There is a need for an accurate, practical, approach which can routinely be applied by project stakeholders to assess and better understand project life cycle energy. Existing LCA studies have not adequately addressed the significance of construction packages and activities in terms of individual life cycle phases (i.e. material, transportation, construction impacts). The unique framework offers a more comprehensive approach compared to previous studies, although its effectiveness is still reliant on capturing comprehensive data from live construction projects. Applying the framework may also help nurture improved project life cycle energy data for purposes such as performance benchmarking and target setting for increased efficiency.

By designing and applying a framework it was possible to capture and assess the significance of construction packages and activities in terms of individual life cycle phases. Material phase impacts were significant in comparison to transportation and construction phase impacts. In particular, the ground and upper floor, external slab and frame were the most significant construction packages due to their reliance on steel and concrete-based materials. Additionally, being present on-site throughout the entire construction phase helped to highlight many challenges with the contractor's practices. For example, the PoW demonstrated no correlation between sub-contractors and their construction activities and the plant register contained data which varied significantly in terms of detail, legibility, and terminology. Consequently, the results identified no direct relationship between construction packages, activities and sub-contractors. Capturing additional indicators (e.g. type and number of plant and equipment per construction activity) may overcome this challenge and improve the granularity of the data. However, this will place additional administrative burden on the contractor and sub-contractors and may only result in minor improvements in the quality of the information.

Previous LCA studies primarily focused towards assessing material phase impacts and the impacts derived from the transportation of plant and equipment and operatives were commonly overlooked. Due to their role within the construction process the contractor has a unique opportunity to capture primary data throughout the transportation and construction phases. The increased capture of this form of data may enable future research to highlight the significance of these life cycle phases and the relationship between them to discover any hidden opportunities for improved efficiency. Improved consideration towards assessing impacts in terms of construction packages as opposed to individual materials may help align data with the requirements outlined within existing forms of environmental measurement (i.e. BREEAM); thus data becoming more useful for contractors.

Although the findings do not provide a proportional view highlighting the significance of individual construction packages relative to total project life cycle impact, they could help improve the contextual understanding of the results and provide a wider perspective of the total project life cycle impacts. In addition the research does not appraise current practices employed by other different sized contractors, though this may help discover common practical challenges towards initial embodied energy assessment which may be included within the scope of future research.

There are limitations with regard to the sample of assessed material and transportation impacts. Reliance upon the ICE material database to assess material impacts and disparity within the contractor current practices (i.e. design drawings and BoQ's) resulted in a proportion of materials within the groundworks, electrical, mechanical and refrigeration construction packages being excluded. In addition, the majority of transportation impacts were not assessed due to inadequacies within the contractor's sign-in sheets primarily due to their content and location on-site. Since the research was limited to an individual UK non-domestic sector project, the results may not be equally applicable within different project types across various geographical locations due to changes in factors such as construction methods, project resource use, production processes, and energy intensities.

From the overall findings it could be argued that efforts to reduce initial embodied energy should be largely directed towards reducing material phase impacts. However, limited awareness surrounds the potential outcomes which may emerge from undertaking such a narrow approach. Selecting low energy materials for example, may influence transportation and construction phase impacts due to changes in the type and number of required project resources. These changes could impact the contractor in terms of their control over pre-construction and on-site construction activities. Nonetheless, as the industry moves towards improved operational energy efficiency, embodied energy is likely to receive greater consideration within UK government policies and forms of environmental measurement. Contractors that can demonstrate improvements in their reduction of embodied energy are likely to have a competitive advantage and will also be well positioned to influence industry standards and policy strategy.

7 ACKNOWLEDGEMENTS

The authors wish to acknowledge the research funding (Grant Reference: EP/G037272/1) and support from the Engineering and Physical Sciences Research Council (EPSRC) and all contractor individuals who contributed to the research findings. Their time and input during data capture are greatly appreciated.

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APPENDIX D DELIVERING IMPROVED INITIAL EMBODIED ENERGY EFFICIENCY (PAPER 4)

Full Reference

Davies, P. J., Emmitt, S., Firth, S.K. (2015) Delivering improved initial embodied energy efficiency during construction. *Sustainable Cities and Society*, 14, 267-279.

Abstract

Energy use during the material, transportation and construction phases up to project practical completion is known as initial embodied energy. Contractors have the opportunity to capture initial embodied energy data and influence performance due to their significant involvement in project procurement and delivery. In this case study practical challenges and opportunities were addressed for delivering improved initial embodied energy efficiency during construction. A revised framework was applied to a live industrial warehouse project to assess the initial embodied energy performance of assorted construction activities, packages and sub-contractors. The practices employed by the contractor on-site were explored and then improved. Results show that material phase impacts represented 95.1% of the total initial embodied energy consumption whereby construction packages predominately containing steel and concrete-based materials (i.e. ground and upper floor, external slab and frame) were most significant. The overall initial embodied impact was deemed greater than the operational impact at the end of the buildings 25-year lifespan. Findings suggest that future project benchmarks and targets should be normalised per site area, as these impacts were found to be significant in this particular case.

Keywords

Initial embodied energy, efficiency, material, transportation, industrial warehouse, construction, contractor.

Paper Type – Journal Paper

Referred Name – Paper 4

1 INTRODUCTION

The UK non-domestic sector is accountable for 18% of the UK's total CO2 emissions, hence providing significant opportunities for CO2 emission and energy consumption reduction (BIS, 2010; Carbon Connect, 2011; Carbon Trust, 2009). Project life cycle energy is derived from operational and embodied energy. Operational energy relates to the energy use during building occupier activity whereas embodied energy relates to the indirect and direct energy inputs required for various forms of construction. Initial embodied energy specifically relates to the energy use during the material, transportation and construction phases up to project practical completion (Cole 1999; Davies, Emmitt, & Firth, 2014; Dixit, Fernandez-Solis, Lavy, & Culp, 2010). Many previous studies have focused on improving operational energy efficiency through developing standardised methods of data capture, benchmarks and exploring common discrepancies between design and actual operational energy performance within buildings (Cabeza, Rincon, Vilarino, Perez, & Castell, 2014; de Wilde, 2014; Firth, Lomas, Wright, & Wall, 2008; Gill, Tierney, Pegg, & Allan, 2011; Menezes, Cripps, Bouchlaghem, & Buswell, 2011; Menezes, Nkonge, Cripps, Bouchlaghem, & Buswell, 2012). However, at present the concept of addressing initial embodied energy is not as advanced within the industry.

Opportunities to address project life cycle energy are typically identified through a life cycle assessment (LCA). Seemingly the availability and accuracy of LCA data is dependent upon many various project factors such as type, scale, location and duration and the decisions undertaken by practitioners in terms of system boundary, data source and calculation method selection (Dixit, Fernandez-Solis, Lavy, & Culp, 2012; Optis & Wild, 2010). Variation amongst these project factors and decisions make it difficult for practitioners to compare data and highlight consistency within results (Cabeza, Barreneche, Miro, Morera, Bartoli, & Fernandez, 2013; Ding & Forsythe, 2013; Treloar, Love, & Iyer-Raniga, 2000).

Understanding the significance of individual project life cycle phases and the relationship between them seems essential for project stakeholders to reduce overall project life cycle energy (Blengini & Di Carlo, 2010; Davies, Emmitt, Firth, & Kerr, 2013b; Langston & Langston, 2008; Optis & Wild, 2010; Sodagar & Fieldson, 2008). Some studies have suggested Building Information Modelling (BIM) will support project stakeholders in the future to identify opportunities to improve energy efficiency through the creation and use of intelligent databases and 3D models (Goedert & Meadati, 2008; Mah, Manrique, Yu, Al-Hussein, & Nasseri, 2010; Vilkner, Wodzicki, Hatfield, & Scarangello, 2007). However, there appears to be limited comprehensive data available (Davies, Emmitt, Firth, & Kerr, 2013b), no coherent method for data capture (BIS, 2010; Dixit, Fernandez-Solis, Lavy, & Culp, 2012), and little incentive for project stakeholders (Hamilton-MacLaren, Loveday, & Mourshed, 2009) to reduce initial embodied energy.

The majority of existing studies have not explored practical approaches to initial embodied energy assessment or addressed the significance of construction packages and activities in terms of individual life cycle phases. Despite the need for improved data and benchmarks (BIS, 2010; Ko, 2010) there appears to be no clear understanding of which project stakeholders are best equip to capture this data and experience the risk and rewards for targeting improved initial embodied energy efficiency (HM Treasury, 2013; RICS, 2012; UK-GBC, 2012). Evidently, project stakeholders may decide going forward to develop internal bespoke methods, based upon own current practices and data, to facilitate initial embodied energy assessment rather than use existing LCA tools (e.g. ATHENA® Impact Estimator, EIO-LCA, Eco-LCA, Ecoinvent) and databases (e.g. DEAM™, GaBi, CFP, IBO, Synergia, ICE, Defra Guide) due to knowledge, user-friendliness and resource availability (Davies, Emmitt, & Firth, 2014; Davies, Emmitt, Firth, & Kerr, 2013b; Scheuer, Keoleian, & Reppe, 2003; Srinivasan, Ingwersen, Trucco, Ries, & Campbell, 2014; Takano, Winter, Hughes, & Linkosalmi, 2014; Van Ooteghem & Xu, 2012). In particular contractors have a vested interest in initial embodied energy and have access to primary data due to their significant involvement in project procurement and delivery (Davies, Emmitt, & Firth, 2013a; Davies, Emmitt, Firth, & Kerr, 2013b; Goggins, Keane, & Kelly, 2010; Li, Zhu, & Zhang, 2010; Monahan & Powell, 2011; RICS, 2010). The study aimed to address the practical challenges and opportunities for delivering improved initial embodied energy efficiency during construction. A literature review helped develop a revised framework intended to assess the initial embodied energy performance of construction activities, packages and sub-contractors relative to a UK industrial warehouse project. The revised framework was applied to a live project to facilitate the capture of primary data.

1.1 INITIAL EMBODIED ENERGY PHASES

1.1.1 MATERIAL PHASE (CRADLE-TO-FACTORY GATE)

Material phase impacts are derived from the consumption of energy (e.g. petrol, diesel, gas, electricity) during the procurement and manufacture of raw materials into finished building materials, products and services. The Inventory of Carbon and Energy (ICE) is a commonly used dataset which highlights the embodied carbon and energy of materials typically used within construction (e.g. concrete, glass, plastic, steel, and timber) (BSRIA, 2011). The embodied coefficients detailed within the dataset are typically used by practitioners in conjunction with material characteristics (i.e. size, volume and weight) derived from a project’s bill of quantities and design drawings (Davies, Emmitt, & Firth, 2014; Davies, Emmitt, Firth, & Kerr, 2013b; Hamilton-MacLaren, Loveday, & Mourshed, 2009; Mah, Manrique, Yu, Al-Hussein, & Nasseri, 2010; Scheuer, Keoleian, & Reppe, 2003). Regardless of project type and location, many previous studies have highlighted the significance of material phase impacts and in particular emphasised the importance of building frame and envelop design in order to help reduce initial embodied energy consumption (Cole & Kernan, 1996; Kofoworola & Gheewala, 2009; Rai, Sodagar, Fieldson, & Hu, 2011; Van Ooteghem & Xu, 2012).

1.1.2 TRANSPORTATION PHASE (FACTORY GATE-TO-SITE GATE)

Transportation phase impacts are derived from the consumption of energy (e.g. petrol, diesel) during transport of material, plant and equipment, and operatives to and from site during the construction phase of a project. Some studies have previously used the publically available data within the 2012 Guidelines to Defra/DECC’s GHG Conversation Factors Company Reporting document (Defra Guide) to assess these impacts (Davies, Emmitt, & Firth, 2014; Williams, Elghali, Wheeler, & France, 2011). The Defra Guide contains a series of GHG conversion factors to allow various activities (i.e. litres of fuel used, number of miles travelled) to be converted into kilograms of carbon dioxide equivalent (kgCO2e) (DEFRA, 2012). Typically to assess these impacts mode and distance of transport data is captured post-construction from various contractor current practices (e.g. sign-in sheets, delivery records) as this data is only available once the construction phase has commenced (Davies, Emmitt, & Firth, 2014; Davies, Emmitt, Firth, & Kerr, 2013b; Hamilton-MacLaren, Loveday, & Mourshed, 2009; RICS, 2012). Seemingly, the majority of previous LCA studies have either: assumed or ignored certain transport data such as distance travelled (Adalberth 1997; Cole, 1999); reported this impact collectively with other life cycle phase impacts such as the construction phase (Cole & Kernan, 1996; Kofoworola & Gheewala, 2009); or overlooked this impact all together (Gustavsson, Joelsson, & Sathre, 2010; Halcrow Yolles, 2010; Iddon & Firth, 2013). Consequently, there is an apparent view within literature that reducing this impact will not result in significant energy reductions for a project or wider industry (Hamilton-MacLaren, Loveday, & Mourshed, 2009; RICS, 2012).

1.1.3 CONSTRUCTION PHASE (SITE GATE-TO-PRACTICAL COMPLETION)

Construction phase impacts are derived from the consumption of energy (e.g. petrol, diesel, gas, electricity) during the installation of building materials, products and services up to project practical completion. Typically to assess these impacts, along with the Defra Guide, construction activity duration, plant and equipment selection, and fuel usage data is captured post-construction from various contractor current practices (e.g. programme of works, plant register), as this data is only available once the construction phase has commenced (Davies, Emmitt, & Firth, 2014; Davies, Emmitt, Firth, & Kerr, 2013b; RICS, 2012). Currently there is a lack of detailed, accurate data within literature which reflects the impact of the construction phase across various projects (Hamilton-MacLaren, Loveday, & Mourshed, 2009), especially as significant time, money and effort are required by practitioners to capture and assess this data. Hence, construction phase impacts are commonly assumed, or even ignored, by practitioners as the impact is viewed to be insignificant in comparison to total project life cycle energy (Gustavsson & Joelsson, 2010; Iddon & Firth, 2013; Pajchrowski, Noskowiak, Lewandowska, & Strykowski, 2014).

2 METHOD

A case study approach was adopted as this provided a useful vehicle for monitoring activities on site in relation to initial embodied energy. One of the researchers was employed by a principal contractor thus providing the opportunity to capture primary data throughout the entire construction phase of the project (lasting 30 weeks). The contractor provided an appropriate sample due to their use of current forms of environmental measurement (i.e. Building Research Establishment Environmental Assessment Method, BREEAM) (BRE, 2011) and overall desire to improve project environmental performance; thus supporting the research by allowing access to primary data.

The case study project was a large design and build industrial warehouse located in the south of England. The project contained two pod offices, a single storey mezzanine office and a large chamber for ambient (10°C) operating and storage use. The main building comprised: prefabricated steel structure; composite roof and cladding panels; precast concrete retaining wall; glazed façade (for the offices); 170 dock levellers; multiple air source heat pumps for heating and cooling. Table 1 illustrates the sample of construction packages, activities and sub-contractors which were explored due to their relative significance towards project value, project duration, operative numbers and quantity of materials used.

Table 1 List of investigated construction packages, activities and sub-contractors

Act Ref.	Sub-contractor Name	Construction Package	Construction Activity	Notes
Act 0	Main Contractor	Project Management	Project Management	
Act 1a	Earthworks	Earthworks	Hardcore	Aggregate (Car Park)
Act 1b	Earthworks	Earthworks	Hardcore	Aggregate (Building)
Act 1c	Earthworks	Earthworks	Hardcore	Aggregate (External Slab)
Act 2a	Foundations	Foundations	Precast Concrete Piles	Precast Concrete
Act 3a	Groundworks	Groundworks	Kerb and Edgings	Battered
Act 3b	Groundworks	Groundworks	Kerb and Edgings	Trief / Titan
Act 3c	Groundworks	Groundworks	Drainage	Land / Storm (high density polyethylene)
Act 3d	Groundworks	Groundworks	Drainage	Car Park (high density polyethylene)
Act 3e	Groundworks	Groundworks	Drainage	External Wall (Clay)
Act 3f	Groundworks	Groundworks	Drainage	Precast Concrete
Act 3g	Groundworks	Groundworks	Drainage	Gatic
Act 3h	Groundworks	Groundworks	Concrete (Pile Caps, Blinding Beds, Column Casing etc.)	In-situ Concrete
Act 4a	Frame	Frame	Steel Columns	
Act 4b	Frame	Frame	Steel Beams	Inc. Bracing, Ties
Act 5a	External Walls	External Walls	Composite Wall Cladding	
Act 5b	External Walls	Roof	Composite Roof Cladding	
Act 6a	Ground Floor	Ground Floor	In-situ Concrete Slab	Warehouse Ground Floor
Act 6b	Ground Floor	Upper Floor	In-situ Concrete Slab	Mezzanine Office Floor
Act 7a	External Slab	External Slab	In-situ Concrete Slab	
Act 8a	Retaining Walls	Retaining Walls	Precast Concrete	
Act 9a	Electrical	Electrical	Electrical Services	Wire
Act 10a	Mechanical	Mechanical	Heating, ventilation and hot water supply insulation	Pipe Work / Duct Wrap
Act 10b	Mechanical	Mechanical	Mechanical Ductwork	
Act 10c	Mechanical	Mechanical	Mechanical Pipework	Gas Pipe
Act 10d	Mechanical	Mechanical	Mechanical Pipework	Water Pipe
Act 11a	Sprinklers	Sprinklers	Pipework Installation	
Act 12a	Syphonic Drainage	Syphonic Drainage	Pipework Installation	
Act 13a	Racking	Racking	Steel Racking Installation	Standard Docks
Act 14a	Dock Levellers	Dock Levellers	Dock Leveller Installation	Scissor Lift
Act 14b	Dock Levellers	Dock Levellers	Dock Leveller Installation	Standard Docks
Act 15a	Internal Walls	Internal Walls	Composite Wall Panels	

2.1 DESK STUDY

Given the paucity of work in this area a decision was taken to apply an existing framework developed by Davies et al. (2014) whereby practices employed by a contractor were used to highlight the significance of initial embodied energy levels of a UK non-domestic sector project. The desk study aimed to address key challenges embedded within the existing framework in order to develop a revised framework which would be explored throughout the case study project.

The framework comprised five key sections (principles, indicators, structure, equations, and alignment) which relied on data captured from practices such as the programme of works, plant register, sign-in sheets and an on-site energy management procedure. Davies et al. (2014) recognised multiple challenges within these practices which reduced the success of the existing framework. In particular the existing framework captured limited transportation data and highlighted no direct link between on-site fuel consumption and construction packages and activities. Table 2 displays the practices and the corresponding improvements to the existing framework derived from the desk study. The revised framework was based upon the same key sections as the existing framework. However, slight changes were made to how the captured data would be correlated between the indicators and structure, and aligned to each indicator in order to satisfy the full data requirements of the revised framework.

Table 2 Contractor current practices explored and corresponding improvements (after Davies et al., 2014)

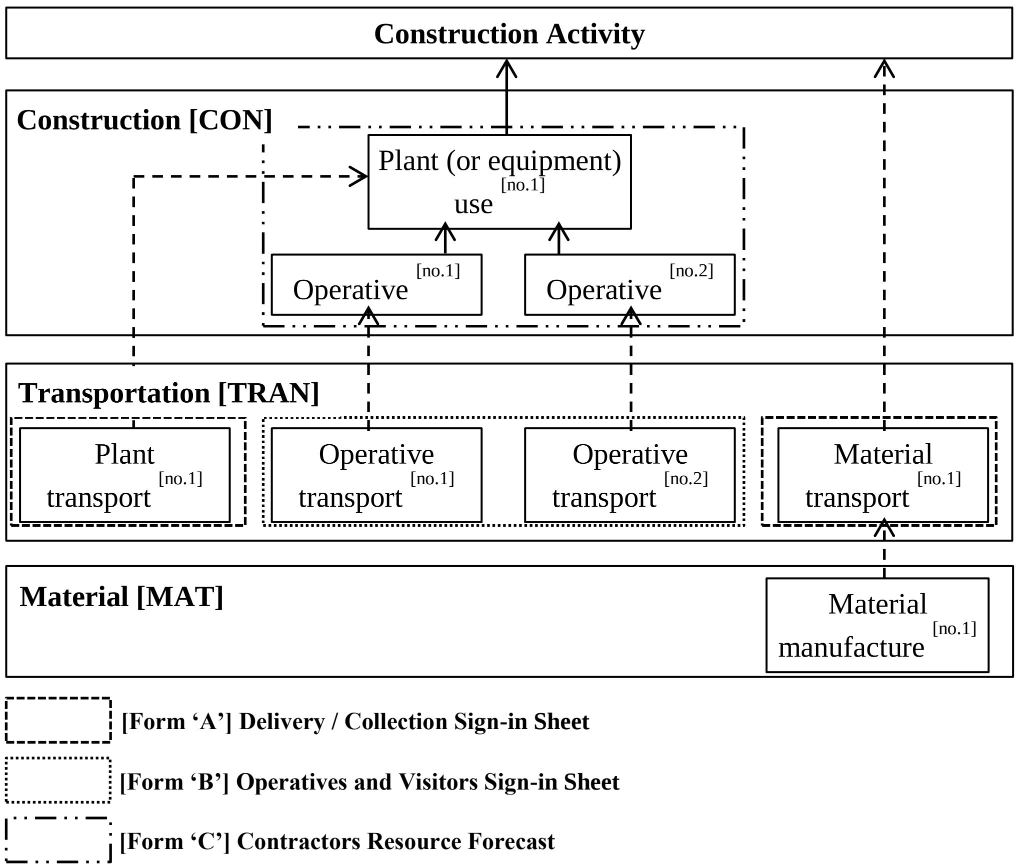
Current Practice Name	Current Practice Purpose	Current Practice Main Challenge	Current Practice Improvements
Programme of Works (PoW)	Review project progression and plan resources for future on-site activities.	No direct link between construction activities and sub-contractors.	[1] Develop a PoW which clearly highlights which sub-contractors are responsible for each construction activity.
Plant Register	Document plant and equipment usage during construction per sub-contractor.	Information varied in terms of content, detail, legibility and terminology.	[2] Develop a single register to collect all plant and equipment data from sub-contractors.
On-site Energy Management Procedure	Record contractor and sub-contractor fuel consumption.	Ambiguity surrounded data in terms of quantity of delivery, data of delivery and fuel consumption during intervals.	[3] Develop a pro forma which enables sub-contractors to provide weekly fuel usage data accompanied with fuel delivery tickets. [4] Develop a check-sheet which correlates all 'pro forma' data highlighting which sub-contractors have (or have not) provided data.
Sign-in Sheets	Capture the movements of sub-contractors, visitors and materials.	Limited data captured due to poor management of site entrance and site set-up.	[5] Develop a new sign-in sheet which correlates material and plant and equipment deliveries (and collections) against specific sub-contractors. [6] Develop a new sign-in sheet which correlates operative movements to and from site against specific sub-contractors. [7] Develop a new sign-in sheet which correlates plant and equipment use on-site to specific construction packages and activities.

The case study project consisted of numerous construction packages, all of which were derived from an assorted number of construction activities. The impact of each construction activity was based upon the associated impact of each life cycle phase (i.e. material, transportation, construction). The impact of each life cycle phase derived from the sub-contractors use of a mixture of project resources such as materials, plant and equipment, and operatives to undertake each construction activity. The impact from these project resources was captured by the contractor current practices. Hence, the overall initial embodied impact of the project was defined in terms of the relationship between construction packages, activities and specific life cycle phases (equation 1, after Davies et al., 2014), thus:

$$EE_{Initial} = \sum_{k=1}^{Nj}\left(\sum_{j=1}^{P}\left(\sum_{i=1}^{3} EE_{ijk}\right)\right) \qquad (1)$$

where i represents the three different project life cycle phases, j represents the construction package, k represents the construction activity, P represents the total number of construction packages, and Nj represents the total number of construction activities. Figure 1 displays an overview of how the embodied impacts of each project life cycle phase was correlated to each construction activity and package for the case study project. Each improvement (i.e. Table 2) contributed to changes in contractor current practice. Three improvements in particular (improvements no. 5-7) contributed to significant changes in contractor current practice and overall alignment of the captured data. These improvements were in the form of three new sign-in sheets (Forms 'A', 'B' and 'C'), developed in order to help highlight the significance of each project life cycle phase relative to specific construction packages, activities and sub-contractors.

Figure 1 Framework structure for capturing project life cycle data per construction activity (after Davies et al., 2014)



The purpose of Form 'A' was to illustrate material, plant and equipment transportation impacts by capturing data such as vehicle type, distance travelled, load capacity and intended recipient. Similarly the purpose of Form 'B' was to identify operative transportation impacts by capturing data such as vehicle type, distance travelled and company name. In contrast the purpose of Form 'C' was to recognise construction impacts by capturing data such as the number and type of operatives, plant and equipment per construction activity.

Data was captured during different intervals from three groups of individuals based upon their role, responsibility and involvement within the project. Forms 'A' and 'B' were filled-in daily by delivery drivers and on-site operatives respectively. Form 'C' was filled-in only once by sub-contractor management (i.e. project manager) when the sub-contractor first began on-site. In order to encourage positive response rates, Forms 'A' and 'B' were located within the security gate house at the entrance of the site accompanied by a brief introduction guide. In terms of Form 'C', an introduction guide and a programme of works was provided to each sub-contractor management in order to connect the correct level of resources required (i.e.

operatives, plant and equipment) for each construction package and construction activity. Overall, Table 3 highlights the alignment of the improved contractor current practices with the requirements of the revised framework. Current practices such as the bill of quantities and design drawings, which are common to all contractors, were required as these practices act as the primary source of information for all material impacts.

Table 3 Alignment of current practices and new sign-in sheets with embodied energy indicators per project life cycle

Life Cycle Phase	Project Resources	Embodied Energy Indicators	Units	Current Practices[a]
Material	Material	Characteristics	type, no., m2, m3, tonne	BoQ, Drawings
Transportation	Material	Distance travelled	miles, km	Form 'A'
		Vehicle used	type, no.	Form 'A'
		Vehicle fuel used	petrol, diesel etc.	Form 'A'
		Vehicle fuel consumption	litres, kWh	Form 'A'
		Vehicle load capacity	tonne, m^3	Form 'A'
		Proportion of load	%	Form 'A'
	Plant and Equipment	Distance travelled	miles, km	Form 'A'
		Vehicle used	type, no.	Form 'A'
		Vehicle fuel used	petrol, diesel etc.	Form 'A'
		Vehicle fuel consumption	litres, kWh	Form 'A'
		Vehicle load capacity	tonne, m^3	Form 'A'
		Proportion of load	%	Form 'A'
	Operatives	Distance travelled	miles, km	Form 'B'
		Vehicle used	type, no.	Form 'B'
		Vehicle fuel used	petrol, diesel etc.	Form 'B'
		Vehicle fuel consumption	litres, kWh	Form 'B'
		Vehicle load capacity	tonne, m^3	Form 'B'
		Proportion of load	%	Form 'B'
Construction	Material + Plant and Equipment + Operatives	Material needed	type, no.	Resource, BoQ, PoW
		Operatives needed	type, no.	Form 'C', Resource, PoW
		Plant needed	type, no.	Form 'C', Plant register, PoW
		Plant duration of use	hrs, days	Plant register, PoW
		Plant fuel type	petrol, diesel etc.	Plant register, Energy Procedure
		Plant fuel consumed	litres, kWh	Plant register, Energy Procedure
		Plant power rating	v, a, watts	Plant register

Notes: [a] Contractors current practices (i.e. data sources): Form 'A','B','C', New Sign-in Sheets; PoW, Programme of Works; BoQ, Bill of Quantities; Resource, Resource Database; Energy Procedure, On-site Energy Management Procedure.

2.2 QUANTITATIVE ANALYSIS

Quantitative data was captured through non-intrusive participant observation throughout the entire construction phase of the project. This method captured detailed primary data resulting from the contractor's current practices and reduced the need for secondary source data derived from post-construction contractor queries. All project information and data was captured, organised and analysed via multiple spreadsheets. Both embodied energy and carbon (i.e. carbon dioxide equivalent, kgCO2e) was measured in order to improve conformity and comparability with previous studies (Dakwale, Raglegaonkar, & Mandavgane, 2011; Dixit, Fernandez-Solis, Lavy, & Culp, 2012; HM Treasury, 2013). Thus, regarding equation 1, embodied energy (EE) would be replaced with embodied carbon (EC).

2.2.1 MATERIAL PHASE DATA

Construction packages consisted of multiple construction activities which comprised of numerous materials. The embodied impact of each material was assessed via the ICE material database. This data was linked to material characteristics (i.e. area, volume, thickness) highlighted within the contractor's bill of quantities and design drawings to obtain the total embodied energy and carbon levels for each construction package.

2.2.2 TRANSPORTATION PHASE DATA

The new sign-in sheets enabled data such as vehicle type, distance travelled and load capacity to be captured from sub-contractors during the construction phase on a daily basis. Transportation phase impacts were calculated by applying this data to the conversion factors addressed within the Defra Guide (DEFRA, 2012).

2.2.3 CONSTRUCTION PHASE DATA

The contractor's on-site energy management procedure enabled fuel type and quantities to be captured from sub-contractors during the construction phase on a monthly basis. Similar to the transportation phase, the embodied impact of the construction phase was calculated by correlating these values against the conversion factors addressed within the Defra Guide (DEFRA, 2012).

3 RESULTS AND DISCUSSION

3.1 QUANTITATIVE ANALYSIS

Table 4 displays the overall reporting scope of the investigation. Despite only 42% of construction activities and 48% of sub-contractors were explored, these represented approximately 81% of the total project value. Table 5 displays the response rates for each of the three new sign-in sheets used to capture primary data throughout the project duration. Forms 'A', 'B' and 'C' captured approximately 92%, 64% and 26% of the total project data available whereby 81%, 69% and 53% of the responses respectively were deemed fully complete.

Table 4 Comparison between total project data and reporting scope

Scope	Activities		Packages		Sub-contractors		Turnover	
	No. [a]	% [b]	No. [a]	% [b]	No. [a]	% [b]	Total [a]	% [b]
Total Project Data	243	100	40	100	31	100	26,886,707	100
Reporting Scope [c]	101	42	15	38	15	48	21,910,933	81
Non-reporting Scope [d]	142	58	25	62	16	52	4,975,774	19

Notes: [a] No.; total number (or value) of construction activities, packages, sub-contractors, and turnover.
[b] Percentage; total number (or value) of construction activities, packages, sub-contractors, and turnover as a percentage of total project data.
[c] Reporting scope; investigated number (or value) of construction activities, packages, sub-contractors, and turnover.
[d] Non-reporting scope; non-investigated number (or value) of construction activities, packages, sub-contractors, and turnover.

Table 5 Response rate and reporting scope per new sign-in sheet (Forms 'A', 'B' and 'C')

Sub-contractor Name	Form 'A'			Form 'B'		Form 'C'	
	MAT	PLANT	Total[a]	OPS	Total[b]	CON	Total[c]
Main Contractor	0	239	239	1,480	1,480	-	-
Earthworks	0	43	43	887	887	1	1
Foundations	82	7	89	119	119	0	0
Groundworks	299	44	343	4,473	4,473	0	0
Frame	95	33	128	189	189	1	1
External Slab	2,561	6	2,567	1,193	1,193	1	1
External Walls / Roof	357	22	379	1,458	1,458	1	1
Retaining Walls	24	6	30	108	108	0	0
Syphonic Drainage	30	8	38	199	199	1	1
Sprinklers	118	17	135	581	581	0	0
Electrical	14	22	36	622	622	0	0
Ground / Upper Floor	2,149	22	2,171	696	696	1	1
Mechanical	48	12	60	498	498	1	1
Dock Levellers	52	11	63	589	589	0	0
Racking	132	15	147	1,810	1,810	1	1
Internal Walls	14	6	20	222	222	0	0
Total sub-contractor data entries[d]	**5,975**	**513**	**6,488**	**15,124**	**15,124**	**8**	**8**
Total project data entries[e]			**7,020**		**23,670**		**31**
Difference[f]			**532**		**8,546**		**23**
Reporting scope (%)[g]			**92**		**64**		**26**
Non-reporting scope (%)			**8**		**36**		**74**
Complete data entries (%)[h]			**81**		**69**		**53**
Non-complete data entries (%)			**19**		**31**		**47**

Notes: [a] Total; total number of material (MAT) and plant and equipment (PLANT) data entries captured by Form 'A'.
[b] Total; total number of operative (OPS) data entries captured by Form 'B'.
[c] Total; total number of sub-contractor construction data entries captured by Form 'C'.
[d] Total sub-contractor data entries; total number of sub-contractor data entries within the reporting scope.
[e] Total project data entries; total number of sub-contractor data entries across reporting scope and non-reporting scope.
[f] Difference; difference between total project data entries and investigated sub-contractor data entries per Form.
[g] Reporting scope; total number of investigated sub-contractor data entries as a percentage per Form.
[h] Responses; total number of complete investigated sub-contractor data entries as a percentage per Form.

3.1.1 MATERIAL PHASE DATA

The material phase was overall responsible for total embodied energy and carbon levels of 558,669.9 GJ and 67,075,540.5 kgCO2e respectively. Table 6 displays the data type, source and calculation methods used to evaluate material phase impacts per individual construction activities whereby Table 7 and Table 8 summarise these impacts per sub-contractor. The results highlighted differences between embodied energy and carbon levels across the construction packages. In terms of embodied energy (Table 7), the most significant construction packages were the ground and upper floors (i.e. in-situ concrete slab) (43.6%), external slab (i.e. in-situ concrete slab) (13.3%) and frame (i.e. steel columns and beams) (12.8%). In relation to embodied carbon (Table 8) the construction packages were responsible for 21.1%, 53.8% and 7.3% respectively. The concrete used within the external slab construction package consisted of traditional in-situ concrete (RC 32/40 with 15% fly ash cement replacement) with steel reinforcement bars (110kg/m3) which was less energy intensive (2.1 MJ/kg) (BSRIA, 2011:40) to produce than steel fibre-reinforcement concrete

(7.8 MJ/kg) (BSRIA, 2011:42) used within the ground and upper floors construction package. The insulated cladding panels included within the external walls and roof construction package was the most energy intensive material to manufacture (101.5 MJ/kg).

Table 6 Material phase impacts (embodied energy and carbon) and calculation methods per construction activity

Data Source[a]	ICE	BoQ		BoQ	BoQ			ICE	ICE					BoQ		
Calculation Method			A x B		B x D	C x D	A x E			C x H	C x J	F x H (or G x H)[e]	G x J		M / P	N / P
Calculation Ref.	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R
Calc' Units[b c]	1	2	3	4	5	6	6	7	8	9	10	11	12	4	9	10
Act Ref. [d]	Density	Thickness	Mass	Area	Volume	Total Mass [Area]	Total Mass [Vol]	EE per Mass	EC per Mass	EE per 1m^{2}	EC per 1m^{2}	EE for Whole Build	EC for Whole Build	Total Build Area	EE per 1m^{2} [Whole]	EC per 1m^{2} [Whole]
Act 1a	2,240.0	0.6	1,388.8	13,879.0	8,605.0	1.93(x10^{7})	-	0.1	0.0	69.4	6.9	9.64(x10^{5})	9.64(x10^{4})	83,675.0	11.5	1.2
Act 1b	2,240.0	0.1	224.0	86,000.0	8,600.0	1.93(x10^{7})	-	0.1	0.0	11.2	1.1	9.63(x10^{5})	9.63(x10^{4})	83,675.0	11.5	1.2
Act 1c	2,240.0	0.5	1,008.0	84,041.0	37,818.5	8.47(x10^{7})	-	0.1	0.0	50.4	5.0	4.24(x10^{6})	4.24(x10^{5})	83,675.0	50.6	5.1
Act 2a	2,300.0	-	-	-	4,249.0	-	9.77(x10^{6})	1.3	0.2	-	-	1.23(x10^{7})[e]	1.58(x10^{6})	83,675.0	147.2	18.8
Act 3a	1,900.0	0.1	237.5	842.0	105.3	2.00(x10^{5})	-	0.5	0.1	123.5	16.4	1.04(x10^{5})	1.38(x10^{4})	83,675.0	1.2	0.2
Act 3b	1,900.0	0.4	741.0	140.4	54.8	1.04(x10^{5})	-	0.5	0.1	385.3	51.1	5.41(x10^{7})	7.18(x10^{3})	83,675.0	0.6	0.1
Act 3c	45.0	-	-	-	3.5	-	1.59(x10^{2})	84.4	2.0	-	-	1.34(x10^{4})[e]	3.19(x10^{2})	83,675.0	0.2	0.0
Act 3d	45.0	-	-	-	6.4	-	2.88(x10^{2})	84.4	2.0	-	-	2.43(x10^{4})[e]	5.75(x10^{2})	83,675.0	0.3	0.0
Act 3e	1,900.0	-	-	-	10.9	-	2.07(x10^{4})	7.9	0.5	-	-	1.64(x10^{5})[e]	1.10(x10^{4})	83,675.0	2.0	0.1
Act 3f	2,300.0	-	-	-	18.5	-	4.26(x10^{4})	1.3	0.2	-	-	5.37(x10^{4})[e]	6.82(x10^{3})	83,675.0	0.6	0.1
Act 3g	7,800.0	-	-	-	12.8	-	9.95(x10^{4})	28.7	2.0	-	-	2.85(x10^{6})[e]	1.94(x10^{5})	83,675.0	34.1	2.3
Act 3h	2,400.0	-	-	-	2,394.0	-	5.75(x10^{6})	1.8	0.2	-	-	1.03(x10^{7})[e]	1.03(x10^{6})	83,675.0	123.2	12.3
Act 4a	7,800.0	-	-	-	163.6	-	1.28(x10^{6})	28.7	2.0	-	-	3.66(x10^{7})[e]	2.49(x10^{6})	83,675.0	437.2	29.7
Act 4b	7,800.0	-	-	-	157.0	-	1.22(x10^{6})	28.7	2.0	-	-	3.51(x10^{7})[e]	2.39(x10^{6})	83,675.0	419.7	28.5
Act 5a	30.0	0.1	3.8	63,280.0	7,910.0	2.37(x10^{5})	-	101.5	4.3	380.6	16.0	2.41(x10^{7})	1.01(x10^{6})	83,675.0	287.9	12.1
Act 5b	30.0	0.1	3.0	83,675.0	8,367.5	2.51(x10^{5})	-	101.5	4.3	304.5	12.8	2.55(x10^{7})	1.07(x10^{6})	83,675.0	304.5	12.8
Act 6a	2,500.0	0.2	375.0	83,675.0	12,551.3	3.14(x10^{7})	-	7.8	0.5	2,906.3	168.8	2.43(x10^{8})	1.41(x10^{7})	83,675.0	2,906.3	168.8
Act 6b	2,400.0	0.2	360.0	1,102.7	165.4	3.97(x10^{5})	-	1.0	0.2	349.2	54.7	3.85(x10^{5})	6.03(x10^{4})	83,675.0	4.6	0.7
Act 7a	2,400.0	0.2	480.0	75,600.0	15,120.0	3.63(x10^{7})	-	2.1	1.0	985.9	477.5	7.45(x10^{7})	3.61(x10^{7})	83,675.0	890.8	431.4
Act 8a	2,000.0	0.3	650.0	1,717.2	558.1	1.12(x10^{6})	-	1.5	0.2	949.0	128.2	1.63(x10^{6})	2.20(x10^{5})	83,675.0	19.5	2.6
Act 9a	7,800.0	-	-	-	23.2	-	1.81(x10^{5})	36.0	2.8	-	-	6.51(x10^{6})[e]	5.12(x10^{5})	83,675.0	77.9	6.1
Act 10a	140.0	-	-	-	35.5	-	4.96(x10^{3})	16.6	1.2	-	-	8.24(x10^{4})[e]	5.96(x10^{3})	83,675.0	1.0	0.1
Act 10b	7,800.0	-	-	-	5.4	-	4.23(x10^{4})	34.4	2.7	-	-	1.46(x10^{6})[e]	1.14(x10^{5})	83,675.0	17.4	1.4
Act 10c	8,600.0	-	-	-	0.4	-	3.40(x10^{3})	40.0	2.2	-	-	1.36(x10^{5})[e]	7.45(x10^{3})	83,675.0	1.6	0.1
Act 10d	8,600.0	-	-	-	0.2	-	1.98(x10^{3})	40.0	2.2	-	-	7.91(x10^{4})[e]	4.33(x10^{3})	83,675.0	0.9	0.1
Act 11a	7,870.0	-	-	-	25.5	-	2.00(x10^{5})	25.0	1.9	-	-	5.01(x10^{6})[e]	3.83(x10^{5})	83,675.0	59.9	4.6
Act 12a	45.0	-	-	-	12.0	-	5.41(x10^{2})	84.4	2.0	-	-	4.56(x10^{4})[e]	1.08(x10^{3})	83,675.0	0.5	0.0
Act 13a	7,800.0	-	-	-	227.5	-	1.77(x10^{6})	21.5	1.5	-	-	3.81(x10^{7})[e]	2.71(x10^{6})	83,675.0	455.9	32.4
Act 14a	7,800.0	-	-	-	66.5	-	5.19(x10^{5})	21.5	1.5	-	-	1.12(x10^{7})[e]	7.94(x10^{5})	83,675.0	133.3	9.5
Act 14b	7,800.0	-	-	-	135.2	-	1.05(x10^{6})	21.5	1.5	-	-	2.27(x10^{7})[e]	1.61(x10^{6})	83,675.0	270.9	19.3
Act 15a	140.0	0.1	14.0	1,413.2	141.3	1.98(x10^{4})	-	16.8	1.1	235.2	14.7	3.32(x10^{5})	2.08(x10^{4})	83,675.0	4.0	0.2

Notes: [a] Data Source; ICE, ICE material database (external literature); BoQ, Bill of Quantities and Design Drawings (contractor current practices).
[b] Calculation Units; 1 (kg/m^{3}); 2 (m); 3 (kg/m^{2}); 4 (m^{2}); 5 (m^{3}); 6 (kg); 7 (MJ/kg); 8 (kgCO_2e/kg); 9 (MJ/m^{2}); 10 (kgCO_2e/m^{2}); 11 (MJ); 12 (kgCO_2e).
[c] EE, Embodied Energy; EC, Embodied Carbon.
[d] Activity Reference keyed to Table 1 contents.
[e] Calculation Method; G x H (Total Mass [Vol] x EE per Mass).

Table 7 Total embodied energy (EE) level of each sub-contractor per life cycle phase

Sub-contractor	Embodied Energy (GJ)[a]					
	MAT[b]	TRAN[b]			CON[b]	Total EE across all life cycle phases
		Material	P&E[c]	Operatives		
Main Contractor	-	-	160.7 (21.6%)	720.1 (15.8%)	1,950.6 (14.1%)	2,831.4 (0.5%)
Earthworks	6,162.6 (1.1%)	-	94.4 (12.7%)	437.1 (9.6%)	6,523.2 (47.0%)	13,217.3 (2.3%)
Groundworks	13,574.2 (2.4%)	695.4 (7.4%)	88.2 (11.8%)	979.6 (21.4%)	2,582.2 (18.6%)	17,919.6 (3.1%)
Foundations	12,313.6 (2.2%)	695.7 (7.4%)	21.6 (2.9%)	40.4 (0.9%)	411.7 (3.0%)	13,483.0 (2.3%)
Frame	71,696.7 (12.8%)	859.8 (9.1%)	63.0 (8.5%)	165.2 (3.6%)	681.8 (4.9%)	73,466.6 (12.5%)
External Walls / Roof	49,565.0 (8.9%)	3,449.7 (36.6%)	62.4 (8.4%)	520.2 (11.4%)	419.3 (3.0%)	54,016.6 (9.2%)
Retaining Walls	1,629.6 (0.3%)	230.8 (2.4%)	8.7 (1.2%)	77.3 (1.7%)	19.5 (0.1%)	1,965.9 (0.3%)
Internal Walls	332.4 (0.1%)	71.3 (0.8%)	4.2 (0.6%)	68.8 (1.5%)	17.8 (0.1%)	494.5 (0.1%)
External Slab	74,535.6 (13.3%)	604.8 (6.4%)	16.0 (2.1%)	244.9 (5.4%)	44.5 (0.3%)	75,445.8 (12.8%)
Ground / Upper Floor	243,565.5 (43.6%)	507.5 (5.4%)	47.9 (6.4%)	198.2 (4.3%)	489.3 (3.5%)	244,808.4 (41.7%)
Electrical	6,514.6 (1.2%)	23.1 (0.2%)	33.1 (4.4%)	259.8 (5.7%)	237.5 (1.7%)	7,068.1 (1.2%)
Mechanical	1,754.1 (0.3%)	79.3 (0.8%)	14.9 (2.0%)	129.3 (2.8%)	18.5 (0.1%)	1,996.1 (0.3%)
Sprinklers	5,011.2 (0.9%)	571.3 (6.1%)	28.6 (3.8%)	68.8 (1.5%)	134.0 (1.0%)	5,813.9 (1.0%)
Syphonic Drainage	45.6 (0.0%)	59.4 (0.6%)	14.8 (2.0%)	47.4 (1.0%)	157.3 (1.1%)	324.5 (0.1%)
Racking	38,143.4 (6.8%)	1,088.9 (11.6%)	60.8 (8.2%)	398.0 (8.7%)	115.4 (0.8%)	39,806.5 (6.9%)
Dock Levellers	33,825.8 (6.1%)	485.3 (5.2%)	25.2 (3.4%)	212.7 (4.7%)	67.0 (0.5%)	34,616.0 (5.9%)
Total EE per life cycle[b]	558,669.9 (100%)	9,422.3 (100%)	744.6 (100%)	4,567.8 (100%)	13,869.5 (100%)	
Total EE all life cycle[d]	558,669.9 (95.1%)	9,422.3 (1.6%)	744.6 (0.1%)	4,567.8 (0.8%)	13,869.5 (2.4%)	587,274.1 (100%)

Notes: [a] Project life cycle phase: MAT, Material; TRAN, Transportation; CON, Construction.
[b] Total EC per life cycle; Total embodied carbon level (%) of each sub-contractor per life cycle phase.
[c] P&E; Plant and Equipment.
[d] Total EC all life cycle; Total embodied carbon level (%) of each sub-contractor across all life cycle phases.

Table 8 Total embodied carbon (EC) level of each sub-contractor per life cycle phase

Sub-contractor	Embodied Carbon ($kgCO_2e$)[a]					
	MAT[b]	TRAN[b]			CON[b]	Total EC across all life cycle phases
		Material	P&E[c]	Operatives		
Main Contractor	-	-	10,954.7 (21.6%)	49,088.6 (15.8%)	150,506.1 (14.1%)	210,549.4 (0.3%)
Earthworks	616,262.4 (0.9%)	-	6,436.4 (12.7%)	29,793.7 (9.6%)	503,315.3 (47.1%)	1,155,807.8 (1.7%)
Groundworks	1,260,484.1 (1.9%)	47,405.3 (7.4%)	6,012.3 (11.8%)	66,775.6 (21.4%)	199,236.6 (18.7%)	1,579,914.0 (2.3%)
Foundations	1,575,359.2 (2.3%)	47,426.1 (7.4%)	1,470.3 (2.9%)	2,750.7 (0.9%)	31,765.9 (3.0%)	1,658,772.4 (2.4%)
Frame	4,876,478.1 (7.3%)	58,607.9 (9.1%)	4,296.1 (8.5%)	11,263.3 (3.6%)	52,606.9 (4.9%)	5,003,252.2 (7.2%)
External Walls / Roof	2,080,264.5 (3.1%)	235,154.5 (36.6%)	4,256.9 (8.4%)	35,457.3 (11.4%)	32,355.1 (3.0%)	2,387,488.3 (3.5%)
Retaining Walls	220,110.7 (0.3%)	15,731.6 (2.4%)	595.3 (1.2%)	5,265.9 (1.7%)	1,504.6 (0.1%)	243,208.2 (0.4%)
Internal Walls	20,774.3 (0.0%)	4,858.3 (0.8%)	288.3 (0.6%)	4,690.6 (1.5%)	1,371.7 (0.1%)	31,983.2 (0.0%)
External Slab	36,095,673.6 (53.8%)	41,227.5 (6.4%)	1,090.0 (2.1%)	16,696.7 (5.4%)	3,275.5 (0.3%)	36,157,963.3 (52.3%)
Ground / Upper Floor	14,180,497.1 (21.1%)	34,595.0 (5.4%)	3,263.3 (6.4%)	13,511.6 (4.3%)	36,441.6 (3.4%)	14,268,308.7 (20.6%)
Electrical	512,116.8 (0.8%)	1,577.6 (0.2%)	2,256.7 (4.4%)	17,710.0 (5.7%)	18,324.2 (1.7%)	551,985.3 (0.8%)
Mechanical	132,057.3 (0.2%)	5,409.0 (0.8%)	1,012.6 (2.0%)	8,813.4 (2.8%)	1,351.4 (0.1%)	148,643.7 (0.2%)
Sprinklers	382,857.4 (0.6%)	38,941.6 (6.1%)	1,950.9 (3.8%)	4,686.5 (1.5%)	10,338.9 (1.0%)	438,775.2 (0.6%)
Syphonic Drainage	1,081.1 (0.0%)	4,048.6 (0.6%)	1,006.2 (2.0%)	3,234.3 (1.0%)	11,813.8 (1.1%)	21,184.0 (0.0%)
Racking	2,714,388.3 (4.0%)	74,223.8 (11.6%)	4,145.5 (8.2%)	27,129.7 (8.7%)	8,906.8 (0.8%)	2,828,794.1 (4.1%)
Dock Levellers	2,407,135.5 (3.6%)	33,082.6 (5.2%)	1,720.5 (3.4%)	14,501.3 (4.7%)	5,166.4 (0.5%)	2,461,606.3 (3.6%)
Total EC per life cycle[b]	67,075,540.51 (100%)	642,289.43 (100%)	50,756.14 (100%)	311,369.06 (100%)	1,068,280.83 (100%)	
Total EC all life cycle[d]	67,075,540.51 (97.0%)	642,289.43 (0.9%)	50,756.14 (0.1%)	311,369.06 (0.5%)	1,068,280.83 (1.5%)	69,148,235.97 (100%)

Notes: [a] Project life cycle phase: MAT, Material; TRAN, Transportation; CON, Construction.
[b] Total EC per life cycle; Total embodied carbon level (%) of each sub-contractor per life cycle phase.
[c] P&E; Plant and Equipment.
[d] Total EC all life cycle; Total embodied carbon level (%) of each sub-contractor across all life cycle phases.

As the original building had been demolished and demolition waste was removed down to ground level before the contractor commenced work, the remaining in-situ ground floor slab, ground beams and foundations were reprocessed (i.e. organised, crushed and transformed into aggregates) by the earthworks sub-contractor on-site; removing the need for virgin material to be transported to site. Approximately 55,000 m3 of aggregate material was reprocessed and used as a sub-base to support the internal and external slabs, drainage and services excavations, and the car park levels.

3.1.2 TRANSPORTATION PHASE DATA

The transportation phase was overall responsible for total embodied energy and carbon levels of 14,734.7 GJ and 1,004,414.6 kgCO2e respectively. Impacts per sub-contractor are summarised within Table 7 and Table 8. In particular material transportation represented 64% of the total transportation phase impacts (Table 9). In terms of embodied impacts, the external walls and roof, racking (i.e. steel racking), and frame construction packages were the most significant; representing 36.6%, 11.6% and 9.1% of the total respectively (Table 7 and Table 8). A total of 357 material movements occurred in order to transport the 16,277.5 m3 of external wall and roof cladding via an articulated lorry (0.99 kgCO2e/km) (DEFRA, 2012:31) to site. In addition a total of 2,561 material movements occurred in order to transport the 15,120 m3 of external slab (i.e. in-situ concrete) via a rigid lorry (0.83 kgCO2e/km) (DEFRA, 2012:31) to site. However, the external wall and roof cladding was sourced from approximately 330 km from site whereas the external slab was only sourced from 10 km from the site.

Table 9 Transportation phase impacts (embodied energy) and corresponding data per sub-contractor

Sub-contractor Name	Form 'A'						Form 'B'		
	Material			Plant and Equipment			Operatives		
	Mov[a]	Dist[b]	EE[c]	Mov[a]	Dist[b]	EE[c]	Mov[a]	Dist[b]	EE[c]
Main Contractor	0	0	0	239	12,450	161	1,480	131,239	720
Earthworks	0	0	0	43	6,804	94	887	79654	437
Foundations	82	47,508	696	7	1,558	22	119	7354	40
Groundworks	299	56,015	695	44	6,495	88	4,473	178,525	980
Frame	95	58,709	860	33	4,525	63	189	30,112	165
External Slab	2,561	49,458	605	6	1,117	16	1,193	44,639	245
External Walls / Roof	357	235,560	3,450	22	4,368	62	1,458	94,796	520
Retaining Walls	24	15,759	231	6	686	9	108	14,079	77
Syphonic Drainage	30	4,056	59	8	1,059	15	199	8647	47
Sprinklers	118	46,716	571	17	2,005	29	581	12,529	69
Electrical	14	1,893	23	22	2,363	33	622	47,348	260
Ground / Upper Floor	2,149	41,502	508	22	3,515	48	696	36,123	198
Mechanical	48	6,489	79	12	1,062	15	498	23,563	129
Dock Levellers	52	33,140	485	11	1,757	25	589	38,769	213
Racking	132	74,352	1,089	15	4,204	61	1,810	72,532	398
Internal Walls	14	4,867	71	6	306	4	222	12,540	69
Total data entries[d]	**5,975**			**513**			**15,124**		
Total distance travelled[e]		**676,021**			**54,274**			**832,449**	
Total embodied energy impact[f]			**9,422**			**745**			**4,568**
Total embodied energy impact (%)[g]			**64**			**5**			**31**

Notes: [a] Mov; total number of data entries (movements to and from site) of materials, plant and equipment, and operatives per sub-contractor.
[b] Dist; total distance travelled (km) of data entries (movements to and from site) of materials, plant and equipment, and operatives per sub-contractor.
[c] EE; total transportation phase impact (embodied energy, GJ) of materials, plant and equipment, and operatives per sub-contractor.
[d] Total data entries; total number of data entries (movements to and from site) from all investigated sub-contractors.
[e] Total distance travelled; total distance travelled (km) of data entries (movements to and from site) from all investigated sub-contractors.
[f] Total embodied energy impact; total embodied energy impact (GJ) from all investigated sub-contractors.
[g] Total embodied energy impact (%); total embodied energy impact from all investigated sub-contractors as a percentage of the total transportation phase impact.

Plant and equipment transportation represented 5% of the total transportation phase impacts. The contractor was responsible for the largest embodied impact (21.6%) followed by the earthworks (12.7%) and groundworks (11.8%) construction packages. Considering the contractor, 198 of the 239 movements related to transfer of construction waste (2,202.7 m3) to a local recycling facility which was located approximately 16 km from the site. Despite the earthworks sub-contractor not requiring any materials to be transported to site, a number of excavators, dumper trucks, bulldozers, and fuel deliveries were required throughout the package duration, as illustrated within Table 10.

Table 10 List of plant and equipment (P&E) used on-site per construction package (sample)

Sub-contractor Name	Construction Package	No. of Operatives and Occupations	No. and Type of P&E used on-site[a]	Duration of P&E use on-site (days)[b]	Duration of P&E use on-site (hours)[c]	P&E fuel capacity (litres)
Main Contractor	Project Management	12 x Supervisors	198 x Skips	150 days	1,200 hours	N/A
			16 x Cabins	150 days	1,200 hours	N/A
			25 x Fuel	150 days	1,200 hours	2,000 liters
Earthworks	Earthworks	1 x Supervisor	11 x Excavators (20t)	120 days	960 hours	400 liters
		22 x Plant Operators	4 x Dumper Trucks (9t)	120 days	960 hours	560 liters
			3 x Bulldozers (6t)	120 days	960 hours	300 liters
			2 x Crusher	120 days	960 hours	130 liters
			1 x Mixer	120 days	960 hours	N/A
			1 x Tractor	120 days	960 hours	400 liters
			21 x Fuel	120 days	960 hours	8,000 liters
Groundworks	Groundworks	3 x Supervisors	4 x Excavator (20t)	135 days	1,080 hours	400 litres
		18 x Plant Operators	4 x Excavator (15t)	135 days	1,080 hours	320 litres
		28 x Labourers	3 x Excavator (9t)	135 days	1,080 hours	200 litres
			4 x Dumper Truck (9t)	135 days	1,080 hours	560 litres
			2 x Roller	135 days	1,080 hours	120 litres
			1 x Telescopic Fork Lift	135 days	1,080 hours	90 litres
			2 x Machine Kerb Lifter	135 days	1,080 hours	N/A
			4 x Petrol Saw	135 days	1,080 hours	N/A
			4 x Skill Saw	135 days	1,080 hours	N/A
			16 x Fuel	135 days	1,080 hours	4,000 litres

Note: [a] t; tonne (size of plant).
[b] Business Days (Monday to Friday).
[c] Business Hours (8 hours per day).

Operative transportation represented 31% of the total transportation phase impacts. A total of 15,124 operative movements occurred, equating to a distance of 832,449 km to and from site. In terms of embodied impacts, the most significant construction packages were the groundworks, contractor and external walls and roof construction packages; representing 21.4%, 15.8% and 11.4% of the total respectively.

3.1.3 CONSTRUCTION PHASE DATA

Throughout the project 349,574 litres of red diesel and 5,402 litres of petrol was delivered and consumed by the contractor and sub-contractors; representing 98.5% and 1.5% of the total embodied impacts respectively. The earthworks, groundworks and contractor were the most significant construction packages signifying 47.0%, 18.6% and 14.1% of the total embodied impacts respectively. The earthworks package took 25 weeks (125 business days) to complete and primarily consisted of a site cut and fill exercise using the reprocessed aggregate material derived from the original building. The plant-intensive construction activities consumed 166,589 litres of red diesel (Table 11). Overall the construction phase was responsible for total embodied energy and carbon levels of 13,869.5 GJ and 1,068,280.8 kgCO2e respectively. Impacts per sub-contractor are displayed within Table 7 and Table 8.

Table 11 Basic project information per sub-contractor during the construction phase

Sub-contractor	Duration[a]	Operative Man Days	Red Diesel Consumption[b]	Petrol Consumption[b]
Main Contractor	150	1,480	49,815	-
Earthworks	120	887	166,589	-
Groundworks	135	4,473	65,944	-
Foundations	35	119	10,514	-
Frame	91	189	17,412	-
External Walls / Roof	106	1,458	10,709	-
Retaining Walls	55	108	498	-
Internal Walls	40	222	454	-
External Slab	110	1,193	742	461
Ground / Upper Floor	64	696	9,251	3,787
Electrical	76	622	6,065	-
Mechanical	66	498	284	220
Sprinklers	80	581	3,422	-
Syphonic Drainage	66	199	3,217	934
Racking	65	1,810	2,948	-
Dock Levellers	70	589	1,710	-
Totals	1,329	15,124	349,574	5,402

[a] Duration; business days (5 days per week).
[b] Fuel Consumption litres.

3.1.4 KEY FINDINGS AND ASSUMPTIONS

The overall findings clearly highlight the importance of material phase impacts (energy and carbon) in comparison to transportation and construction phase impacts (Table 12). Construction packages which predominately contained steel and concrete-based materials (i.e. ground and upper floor, external slab and frame) were the most significant, reflecting similar results to those of Cabeza, Barreneche, Miro, Morera, Bartoli, & Fernandez (2013), Chen, Burnett, & Chau (2001), Goggins, Keane, & Kelly (2010) and Halcrow Yolles (2010). Decisions to use the original building as a source of aggregates for the earthworks package enabled certain material transportation impacts to be offset by additional construction impacts as on-site fuel use primarily related to the reprocessing and transformation of the demolition building into useable aggregates.

Throughout the data capture and analysis certain assumptions were necessary due to the complex nature of the construction project. It was assumed that only 80% of the total material scope within the groundworks, mechanical and electrical construction packages was captured primarily due to data discrepancy (i.e. measurement and specification details) within the design drawings and BoQ’s, the restricted selection of materials addressed within the ICE material database, and overall time constraints for managing large quantities of data. Thus, it is likely impacts per construction package and for the overall project would be greater than reported.

Table 12 Total embodied energy and carbon results per project life cycle phase

Life Cycle Phase	Embodied Energy (GJ)	Ratio (%)	Embodied Carbon (kgCO2e)	Ratio (%)
Material [MAT]	558,669.9	95.1	67,075,540.5	97.0
Transportation [TRAN]	14,734.7	2.5	1,004,414.6	1.5
Construction [CON]	13,869.5	2.4	1,068,280.8	1.5
Total	**587,274.1**	**100**	**69,148,235.9**	**100**

3.2 CHALLENGES FOR IMPROVED INITIAL EMBODIED ENERGY EFFICIENCY

Many practical challenges for delivering improved initial embodied energy efficiency were identified as a consequence of the study. Primarily these challenges related to capturing, normalising and organising data.

3.2.1 CAPTURING DATA

Correlating material data between the contractor current practices and the embodied coefficients within the ICE material database proved difficult. Data was represented in various inconsistent forms (i.e. weight per unit, weight of total, length, kg/m2) which were not easily transferable for computation; highlighting the need for further standardisation of units for environmental measurement (BIS, 2010; Carbon Connect, 2011). Previous studies have also questioned the validity of the ICE material database to truly reflect the environmental impact during material manufacture due to the reliance upon secondary sourced data and narrow system boundaries (Doran & Anderson, 2011; Fieldson & Rai, 2009). Although, HM Treasury (2013) and RICS (2012) previously argued any it is important to reduce environmental impacts than necessitate on the accuracy of results. Seemingly there is a need for additional research to improve understanding of the material phase impacts whereby the recent development of the CEN TC 350 Standards and improvements to Environmental Product Declarations (EPD’s) for construction materials could potentially fulfil this requirement, as previously noted by BIS (2010) and Halcrow Yolles (2010).

3.2.2 NORMALISING DATA

Within existing studies and forms of environmental measurement (e.g. Simplified Building Energy Model, Environmental Performance Certificate; BREEAM, Carbon Profiling) operational energy consumption is typically normalised relative to building area (BICS, 2006; BIS, 2010; BRE, 2011; DECC, 2009a; RICS, 2010). However, the results of the study question whether this particular approach is suitable to address embodied energy as a significant proportion of impacts originated from the site area (i.e. total building and infrastructure area). As the industrial warehouse was intended for the delivery and storage of grocery retail products, the bulk of the site area (56.2%) was taken up by hard landscaping (i.e. kerbs, edges, road infrastructure, pathways, and delivery and loading bays). The construction activities and packages within this area (i.e. external slab, earthworks, groundworks and main contractor packages) contributed to 18.6% and 56.6% of the total initial embodied energy and carbon levels respectively. Typically these embodied impacts have been overlooked within previous studies (Cole & Kernan, 1996; Fay, Treloar, & Raniga, 2000; Kofoworola & Gheewala, 2009; Rai, Sodagar, Fieldson, & Hu, 2011; Scheuer, Keoleian, & Reppe, 2003), although it seems impacts derived from the site area need to be considered to understand a project’s true life cycle impact and to create more meaningful benchmarks and targets for project stakeholders to drive improved initial embodied energy efficiency, a requirement previously supported by BIS (2010) and Ko (2010).

3.2.3 ORGANISING DATA

Within the revised framework Form 'C' was designed to provide a fundamental link between transportation and construction impacts per construction activity for each sub-contractor. However, significant issues emerged during the use of Form 'C' as information captured from the sub-contractors was either incomplete or varied in terms of content, detail and terminology. Hence, it was not possible to accurately assess the embodied impacts for all construction activities. In addition, from the responses alone, it proved difficult to accurately correlate each construction activity on the programme of works (PoW) to each sub-contractor. Primarily this was due to the contractor needing to react to unforeseen circumstances during the construction phase (i.e. changes in design, materials, construction methods and techniques) which ultimately impacted on the number and duration of many construction packages and activities; consequently the PoW was updated regularly. Further, occasionally where no or incomplete responses were received from sub-contractors the contractor was required to verbally confirm the outstanding data. Thus from the data alone, the method does not appear to support autonomy of capturing and assessing initial embodied impacts without a contractor employee being present to monitor and manage the process.

3.3 OPPORTUNITIES FOR IMPROVED INITIAL EMBODIED ENERGY EFFICIENCY

Many practical opportunities for delivering improving initial embodied energy efficiency were identified as a consequence of the study. These opportunities relate to individual material, transportation, and construction phases and overall project life cycle performance.

3.3.1 MATERIAL PHASE PERFORMANCE

Due to the prevailing impact of the material phase, seemingly project stakeholders should focus efforts towards material selection in order to significantly reduce a project's initial embodied impact, a view previously supported by Scheuer, Keoleian, & Reppe (2003) and Treloar, Love, & Holt (2001). However, it appears consideration should not simply be driven towards selecting materials with low embodied coefficient values (energy or carbon) as material quantities and characteristics such as volume (m3) and density (kg/m3) also need consideration, as noted by Halcrow Yolles (2010) and Harris (2008).

Similar to Goggins, Keane, & Kelly (2010) and Habert & Roussel (2009), the findings suggest significant embodied energy savings could be achieved through the selection of alternative concrete mix design and performance specifications. Considering the ground and upper floor package, if a traditional in-situ concrete with steel reinforcement bars was selected as an alternative to the steel fibre-reinforcement concrete used, this could have reduced the package embodied energy level by 73% (i.e. from 243,565.5 GJ to 64, 835.7 GJ). However, the contractor confirmed that the specific concrete specification was selected as it allowed the incorporation of an additional rapid hardening agent which reduced concrete curing time and allowed following construction packages (e.g. the sprinklers and syphonic drainage) to commence work shortly after the completed concrete pour. In this instance, it appears the contractor's overarching commitment towards project programme was more important than selecting an environmental alternative, a common approach for project stakeholders as noted by Anderson & Mills (2002) and Sodagar & Fieldson (2008). Despite the apparent environmental benefits, selecting alternative low embodied impact materials may result in changes to construction techniques, procurement methods, and building maintenance cycles (Buchanan & Honey, 1994; Davies, Emmitt, Firth, & Kerr, 2013b; Fieldson & Rai, 2009).

3.3.2 TRANSPORTATION PHASE PERFORMANCE

Due to the project's location near many road and rail transportation links, the project team had many options when sourcing materials, plant and equipment, and operatives. In particular, the project benefited from the use of locally sourced concrete within the ground and upper floor, external slab and groundworks packages as this was sourced approximately 10 km away from site. Despite concrete deliveries representing 81.4% of total number of deliveries to site, these deliveries only signified 12.2% of the total transportation phase impacts. In comparison, the 357 deliveries of external walls and roof insulation were sourced over 330 km which represented 36.6% of the total transportation phase impacts. The environmental and cost benefits experienced by contractors for using locally sourced materials, fuel efficient vehicles and consolidation centres to increase delivery reliability have been previously highlighted in many studies (BRE, 2003; Citherlet & Defaux, 2007; Ko, 2010; Sodagar & Fieldson, 2008), though as emphasised by Halcrow Yolles (2010), transportation phase impacts are site specific thus it is difficult to identify significant trends across different studies.

3.3.3 CONSTRUCTION PHASE PERFORMANCE

Red diesel was used as the primary energy source to power initial on-site operations as opposed to electricity from the main electrical grid, a common approach previously discussed by Monahan & Powell (2011). The contractor confirmed that this decision was due to the high initial capital cost for the main electrical grid supply, the limited lead-in time between obtaining the project contract and starting the on-site construction phase, and the difficulty in agreeing a practical location for the supply that would benefit the temporary on-site accommodation and main building positioning. Seemingly, specifying fuel efficient plant, accommodation and improving on-site logistics and coordination of activities would provide energy and cost reduction benefits for contractors, as previously highlighted by ERA (2014) and Ko (2010).

3.3.4 PROJECT LIFE CYCLE PERFORMANCE

Many previous studies have demonstrated the significance of operational energy in comparison to embodied energy (Adalberth, 1997; Cole & Kernan, 1996; Kofoworola & Gheewala, 2009; Scheuer, Keoleian, & Reppe, 2003). However, for this particular explored project, initial embodied energy appears more important than operational energy.

Table 13 demonstrates a comparison between the impacts of the project's life cycle phases (embodied and operational) throughout the building lifespan. Embodied impact data (energy and carbon) was compared against the SBEM (Simplified Building Energy Model) data provided by the contractor which identified the predicted operational performance of the building per annum. As operational impacts originate from the building footprint only, these impacts were normalised across the entire site area in order to equally compare the total sum of all project embodied and operational impacts. Within previous LCA studies building lifespan can range between 25-75 years (Cole & Kernan, 1996; Gustavsson, Joelsson, & Sathre, 2010; Rai, Sodagar, Fieldson, & Hu, 2011; Scheuer, Keoleian, & Reppe, 2003), although in this instance due to the project scope and intentions of the client and developer, the contractor confirmed that the building had an expected lifespan (i.e. design life) of 25 years. Hence, on this occasion the initial embodied impact would remain greater than the operational energy impact at the end of the building's life. In particular it would take approximately 31 years and 28 years for the operational impact to exceed the initial embodied energy and carbon impacts respectively. This finding challenges the view previously addressed by Gustavsson, Joelsson, & Sathre (2010) stating operational energy should be considered before embodied energy as it represents the largest share in project life cycle energy. Seemingly, the evidence questions the current direction of industry directives (DECC, 2009b; DIAG, 2011; Legislation, 2008) and project stakeholders (Davies, Emmitt, Firth, & Kerr, 2013b; Sodagar & Fieldson, 2008; Tassou, Hadawey, & Marriott, 2011) as both are primarily focused towards reducing operational energy as opposed to total project life cycle energy. The findings emphasise the importance of building lifespan and project type when considering the true environmental impact of a project, as previously noted by Adalberth (1997), Chau, Yik, Hui, Liu, & Yu, (2007) and Cole (1999). Importantly however due to the scope of this study the comparison does not take into consideration the impact of recurring embodied energy (Treloar, McCoubrie, Love, & Tyer-Raniga, 1999; Chen, Burnett, & Chau, 2001), the decarbonisation of the UK national grid (DECC, 2012), the variation between predicted and actual operational energy performance of buildings (Menezes, Cripps, Bouchlaghem, & Buswell, 2011); and the time value of carbon (Karimpour, Belusko, Xing, & Bruno, 2014); all of which would alter the significance and the relationship between both project life cycle impacts.

Table 13 Comparison between embodied and operational impacts (energy and carbon) throughout building lifespan

	Energy (GJ)		Carbon (kgCO$_2$e)	
	Embodied	**Operational**	**Embodied**	**Operational**
Site Area [a]	191,074.0	191,074.0	191,074.0	191,074.0
Total Impact[bc]	587,274.1	19,245.3	69,148,235.9	2,501,882.5
Impact / Site Area[de]	3.07	0.10	361.89	13.09
Impact End of Year 1 (%Ratio)	587,274.1 (96.8%)	19,245.3 (3.2%)	69,148,235.9 (96.5%)	2,501,882.5 (3.5%)
Impact End of Year 10 (%Ratio)	587,274.12 (75.32%)	192,452.50 (24.68%)	69,148,235.9 (73.4%)	25,018,825.0 (26.6%)
Impact End of Year 25 (%Ratio)	587,274.1 (55.0%)	481,131.3 (45.0%)	69,148,235.9 (52.5%)	62,547,062.5 (47.5%)
Impact End of Year 50 (%Ratio)	587,274.12 (37.9%)	962,262.50 (62.1%)	69,148,235.9 (35.6%)	125,094,125.0 (64.4%)
Operational Impact > Embodied Impact[f]	-	30.53 Years	-	27.64 Years

Notes: [a] Units; Site Area (m^2).
[b] Total Impact; Embodied Energy and Carbon calculated through case study (i.e. actual); Operational Energy and Carbon captured from SBEM (i.e. predicted).
[c] Units; Energy (GJ), Carbon (kgCO2e).
[d] Impact; Embodied and Operational impacts normalised over site area.
[e] Units; Energy (GJ/m^2), Carbon (kgCO2e/m^2).
[f] Years; Number of Years it takes for the predicted Operational Impact to outweigh the actual Embodied Impact.

4 CONCLUSIONS

The study demonstrated practical challenges and opportunities for delivering improved initial embodied energy efficiency from an industrial warehouse project located in the south of England. Depending on procurement methods the approach can potentially be replicated by contractors with similar current practices (i.e. programme of works, plant register, bill of quantities, design drawings, and sign-in sheets) as the system boundary, data source and calculation methods selected have been presented. Seemingly contractors can help provide initial embodied energy data for targeting improved energy efficiency within future projects, although in this instance, challenges related to capturing, normalising and organising data existed.

In this case study material phase impacts represented a significant proportion (95.1%) of the total initial embodied energy consumption, with construction packages predominately containing steel and concrete-based materials (i.e. ground and upper floor, external slab and frame) being most significant. Thus the need to improve initial embodied energy efficiency should be primarily focused towards selecting alternative lower embodied impact materials within these packages, although the results indicate that material quantities, characteristics and performance criteria also need to be considered. Selecting alternative low embodied impact materials may result in changes to on-site construction techniques, procurement methods, operational energy efficiency, architectural form, and building maintenance cycles. Despite transportation and construction phase impacts only representing 4.9% of the total initial embodied energy performance, the results from this case study highlight the importance of sourcing high embodied impact materials (e.g. concrete) locally and reducing the reliance upon red diesel fuelled plant-intensive construction activities (e.g. earthworks) in order to improve initial embodied energy efficiency.

Significant embodied impacts were derived from outside the building footprint area. Despite these impacts being commonly overlooked within existing studies and forms of environmental measurement, they reflect the project's true life cycle impact, and therefore need to be integrated into future project benchmarks and targets. This will allow project stakeholders to drive improved initial embodied energy efficiency. Similarly, the overall initial embodied impact was deemed greater than the operational impact at the end of the building's life. Hence there is a need to address total project life cycle impacts as opposed to just operational impacts in order to make significant reductions in energy and carbon levels throughout building design, construction and operation.

Although the results are derived from one large project within a principal contractor's significant project portfolio, the findings do provide a unique indication of the complexity of delivering initial embodied energy during the construction phase. In future research it may be insightful to examine the views and current practices of different project stakeholders to determine which are best equipped to capture, assess and predict initial embodied energy performance during different stages of project development. Similarly it may be informative to investigate the relationship between operational and initial embodied energy performance across different project types in order to improve understanding of how to reduce overall project life cycle impact.

5 ACKNOWLEDGEMENTS

The authors wish to acknowledge the research funding (Grant Reference: EP/G037272/1) and support from the Engineering and Physical Sciences Research Council (EPSRC) and the many individuals attending the site who provided data, whose time and efforts are greatly appreciated.

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APPENDIX E ALIGNMENT OF RESEARCH SUB-OBJECTIVES

The tables below align the contents of each research paper with the research sub-objectives.

Research Paper 1 Contents	Sub-objective Alignment
Introduction	
On-site energy management drivers	Sub-objective 1.4
Non-domestic sector	Sub-objective 1.1
On-site energy management current practices	
Energy phases	Sub-objective 1.3
On-site monitoring	Sub-objective 1.2
Method	
Results and discussion	
Desk study	Sub-objective 2.1
Quantitative analysis	Sub-objective 2.1
Model development	Sub-objective 2.1
Model assessment	Sub-objective 2.1
Model effectiveness	Sub-objective 2.1
Interviews	
On-site energy management drivers	Sub-objective 1.4
On-site energy management current practices	Sub-objective 2.1
On-site energy management challenges	Sub-objective 1.5
On-site energy management opportunities	Sub-objective 1.6
Conclusions	Sub-objective 5.1

Research Paper 2 Contents	Sub-objective Alignment
Introduction	
Role of the contractor	
Defining and assessing embodied energy	
Drivers for contractors	
Policy and legislative	Sub-objective 1.4
Financial and business	Sub-objective 1.4
Challenges for contractors	
Financial and business	Sub-objective 1.5
Design and technical	Sub-objective 1.5
Opportunities for contractors	
Financial and business	Sub-objective 1.6
Design and technical	Sub-objective 1.6
Method	
Results and discussion	
Review of existing LCA studies	Sub-objective 1.3
Appraisal of contractor current practices	Sub-objective 2.2
Conclusions	Sub-objective 5.1

Research Paper 3 Contents	**Sub-objective Alignment**
Introduction	
Project life cycle energy	Sub-objective 1.3
Life cycle assessment (LCA)	
LCA system boundaries	Sub-objective 1.2
LCA calculation methods	Sub-objective 1.2
Process-based method	Sub-objective 1.2
Input-output-based method	Sub-objective 1.2
Hybrid-based method	Sub-objective 1.2
LCA data sources	Sub-objective 1.2
LCA assumptions	Sub-objective 1.2
Method	
Desk Study	
Framework principles	Sub-objective 3.1
Framework indicators	Sub-objective 3.1
Framework structure	Sub-objective 3.1
Framework equations	Sub-objective 3.1
Framework alignment	Sub-objective 3.1
Quantitative analysis	
Material data	Sub-objective 2.2
Transportation data	Sub-objective 2.2
Construction data	Sub-objective 2.2
Results and discussion	
Quantitative analysis	
Material data	Sub-objective 3.2
Transportation data	Sub-objective 3.2
Construction data	Sub-objective 3.2
Key findings and assumptions	Sub-objective 3.2
Challenges for initial embodied energy assessment	
Programme of works	Sub-objective 4.1
Plant register	Sub-objective 4.1
On-site energy management	Sub-objective 4.1
Sign-in sheets and resource database	Sub-objective 4.1
Environmental reporting	Sub-objective 4.1
Conclusions	Sub-objective 5.1

Research Paper 4 Contents	Sub-objective Alignment
Introduction	
Initial embodied energy phases	
Material phase (cradle-to-factory gate)	Sub-objective 1.3
Transportation phase (factory-to-site gate)	Sub-objective 1.3
Construction phase (site gate-to-practical completion)	Sub-objective 1.3
Method	
Desk Study	Sub-objective 3.1
Quantitative analysis	Sub-objective 3.1
Material data	Sub-objective 3.1
Transportation data	Sub-objective 3.1
Construction data	Sub-objective 3.1
Results and discussion	
Quantitative analysis	
Reporting scope and response rate	Sub-objective 3.2
Material data	Sub-objective 3.2
Transportation data	Sub-objective 3.2
Construction data	Sub-objective 3.2
Key findings and assumptions	Sub-objective 3.2
Challenges for improved initial embodied energy efficiency	
Capturing data	Sub-objective 4.1
Normalising data	Sub-objective 4.1
Organising data	Sub-objective 4.1
Opportunities for improved initial embodied energy efficiency	Sub-objective 4.1
Material phase performance	Sub-objective 4.1
Transportation phase performance	Sub-objective 4.1
Construction phase performance	Sub-objective 4.1
Project life cycle performance	Sub-objective 4.1
Conclusions	Sub-objective 5.1

APPENDIX F RESEARCH TRAINING COURSES AND PRELIMINARY STUDIES

The table below highlights the key academic and industry-based training courses which were undertaken throughout the research to improve the RE's professional development, academic knowledge, and industry competency.

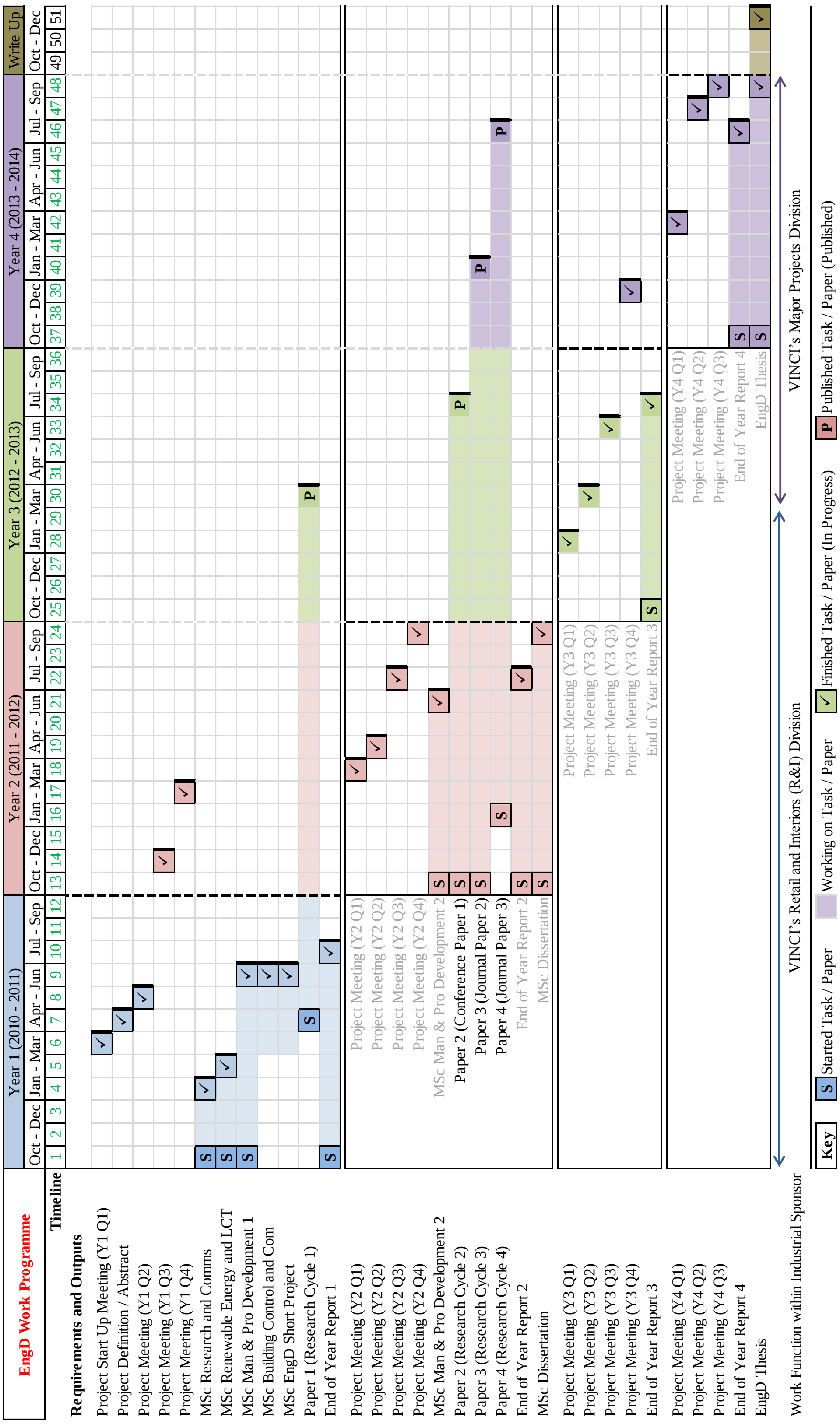
No.	Name	Targeted Skill	Type	Hours	Date
1	Getting the Most out of Supervision	Personal	Academic	3	Mar-11
2	Non-parametric Statistics	Research Methods	Academic	3	Mar-11
3	EcoBuild 2011	Environmental	Seminar	16	Mar-11
4	Time and Self-management	Personal	Academic	3	Apr-11
5	Managing your PhD as a Project	Personal	Academic	3	May-11
6	RefWorks	Research Methods	Academic	8	May-11
7	HS&E Awareness (Managers)	Health and Safety	Industry	16	May-11
8	The Effective Researcher	Research Methods	Academic	16	Jun-11
9	Organisation Induction	Personal	Industry	8	Jun-11
10	Getting Articles Published for Researchers	Research Methods	Academic	3	Jul-11
11	What is a Literature Review?	Research Methods	Academic	3	Jul-11
12	Step Up Safety Leadership Workshop (Supervisors)	Health and Safety	Industry	8	Oct-11
13	The Enterprising Researcher	Personal	Academic	8	Nov-12
14	Successful Interviews	Research Methods	Academic	3	Jan-13
15	Understanding Conferences	Research Methods	Academic	3	Mar-13
16	Planning and Programming	Technical	Industry	8	Mar-13
17	EcoBuild 2013	Environmental	Seminar	16	Mar-13
18	Control of Temporary Works	Technical	Industry	8	Apr-13
19	Setting Out for Engineers	Technical	Industry	24	Apr-13
20	Public Engagement and Research	Research Methods	Academic	8	May-13
21	Time Management	Personal	Industry	8	Jun-13
22	Team Work	Personal	Industry	8	Jun-13
23	Priority One	Technical	Industry	3	Jul-13
24	Sustainable Building Conference 2013	Environmental	Conference	24	Jul-13
25	Falsework Design and Appreciation	Technical	Industry	8	Oct-13
26	Site Environmental Awareness Training Scheme	Environmental	Industry	8	Jan-14
27	Site Management Safety Training Scheme	Health and Safety	Industry	40	Jan-14
28	EcoBuild 2014	Environmental	Seminar	16	Mar-14
29	Embodied Carbon Week 2014	Environmental	Seminar	10	Apr-14

The table below highlights the key findings of the preliminary study into operational energy consumption, which are summarised per operational energy category (i.e. drivers, definitions, current performance, current practices, challenges, and opportunities).

Category	Findings
Drivers	- Energy Performance Certificates (EPCs) relay the design energy performance whereas Display Energy Certificate (DECs) demonstrates the actual operational energy performance of a building (BIS, 2010); - During 2008 EPCs became mandatory for all non-domestic buildings constructed, sold or let and DECs became obligatory for all frequently visited public authority and institution buildings with a total floor area over 1,000m^2 (CLG, 2008a; CLG, 2012b).
Definitions	- Net energy relates to the balance between the energy consumed by a building and the energy produced by its renewable energy systems (Lenzen and Munksgaard, 2002; Hernandez and Kenny, 2010); - A Low Carbon-Zero Energy Building (LC-ZEB) is whereby the total energy consumed in the building operation and the embodied energy of the building systems and materials are equal to or less than the total energy produced by the buildings renewable energy systems, in relation to the whole building lifespan (CLG, 2007; Hernandez and Kenny, 2010); - A net-zero energy building is whereby the energy used and sold to the national electrical grid by a building is balanced (Torcellini et al., 2006; Hernandez and Kenny, 2010);
Current Performance	- The environmental impact of any building is dependable of the overall building's location, design, construction and operational energy use (Harris, 1999); - Operational energy is influenced by variations in building use pattern, changes in seasons and climatic conditions, plus the general efficiency of the services (Cole and Kernan, 1996); - Within the UK, the total operational energy use of buildings equates to approximately half the UK total CO_2 emissions per annum and energy is now being demanded for much longer periods (Hinnells, 2008; Rai et al., 2011); - The CO_2 resulting from Tesco operations, is approximately 20% of the total carbon emissions resulting from the whole UK retail sector (Tesco PLC, 2007).
Current Practices	- Refrigeration systems utilised within UK supermarkets stand for a large part of the refrigeration sector whereby 5% of UK national electrical output is utilised via this sector (Davies and Caretta, 2004); - Heating, Ventilation and Air Conditioning (HVAC) systems within UK supermarkets are typically responsible for 15% to 25% of total building energy use, and is influenced by the location of the store, system design and controls (Tassou et al., 2011).
Challenges	- Current measures for accounting data are insufficient due to reasons such as: momentary reliance, business focus, numerical quantification, capitalist orientation, and technical accounting practices (Jones, 2010); - At present there is still limited investment in low carbon buildings, even though investors: expect an increasing disparity in market valuation between low carbon and traditional build type; foresee continual modifications to Building Regulations; and expect increased demand from end users (BIS, 2010).
Opportunities	- BIS (2010) suggested that increased development and modernisation of techniques such as benchmarking and continuous improvement in addition to improved case studies and databases defining embodied carbon data, energy consumption data, post occupancy evaluations, and operational costs; are all needed for project decision makers to develop enhanced energy efficient developments; - Incorporating simply energy efficiency solutions such as automatic monitoring equipment, improved lighting controls, and voltage optimisation units can provide energy and cost savings for an organisation (Carbon Connect, 2011); - The use of smart metering should encourage consumers to reduce their energy consumption by providing better information and transparency to facilitate conservative electricity consumption behaviour (Firth et al., 2008; Gill et al., 2011); - Operational energy and building performance can be appraised in use, through a Post Occupancy Evaluation (POE), to highlight further opportunities to improve building efficiency and control for occupiers (Bordass and Leaman, 2001; Bordass et al., 2001a; Bordass et al., 2001b; Bordass and Leaman, 2005a; Bordass and Leaman, 2005b).

APPENDIX G ENGD WORK PROGRAMME

The programme below demonstrates all of the outputs needed to fulfil the requirements of the EngD.



APPENDIX H FUTURE RESEARCH

The content below presents the basis of future research papers, currently in process, that have directly stemmed from the development of the research project and the RE's active involvement within the industrial sponsor (i.e. contractor).

AN INTEGRATED APPROACH TOWARDS THE REDUCTION OF INITIAL EMBODIED ENERGY IN CONSTRUCTION PROJECTS (PAPER 5)

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Abstract

Initial embodied energy is derived from energy used during the material, transportation and construction phases up to project practical completion. Project stakeholders have varied interest in initial embodied energy performance and access to primary data due to different involvements within project procurement, delivery and forms of environmental measurement. In this case study practical challenges and opportunities for delivering an integrated approach towards reducing initial embodied energy consumption during different phases (i.e. tender, pre-construction and on-site construction) of project development were identified via monitoring live construction projects. The perspectives of multiple project stakeholders (i.e. clients, designers, contractors, and sub-contractors) were addressed through a variety of data collection methods, including desk studies and a quantitative analysis. Data exploration provided evidence for the design of a unique energy method statement intended to provide project decision makers with improved practical awareness and application for reducing initial embodied energy consumption during different phases of project development. Findings suggest that energy and cost savings can be achieved through better predictions and understanding of energy on-site. Improved benchmarks and incentives could support initial embodied energy reduction though potential changes in the performance of different life cycle phases are unclear.

Keywords

Initial embodied energy, reduction, contractor, client, method statement, prediction.

Journal

Architectural Engineering and Design Management

INVESTIGATING ON-SITE TEMPORARY LIGHTING DESIGN IN CONSTRUCTION PROJECTS: A CASE STUDY (PAPER 6)

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Abstract

Three forms of temporary lighting are commonly used during on-site construction; task, emergency, and safety. Task lighting is specified by the sub-contractor and deemed 'job specific' whereas emergency and safety lighting is typically supplied and maintained by the contractor within any place on-site where there could be a potential risk to the health and safety of individuals. Technological advances have provided many options for contractors when specifying the performance criteria for temporary lighting design. A case study is presented of a large UK principal contractor's on-site management of alternative temporary lighting designs (traditional incandescent and light-emitting diode lighting) during the construction phase of a UK non-domestic sector project. The practical benefits and burdens of the alternative temporary lighting designs were examined via on-site monitoring of their performance in terms of transportation requirements, installation methods, and energy consumed during the construction phase of a UK non-domestic sector project. Findings revealed significant disparity of illumination levels, energy use, and associated operational cost between the alternative temporary lighting designs in order to satisfy the performance criteria.

Keywords

Initial embodied energy, temporary lighting, design, contractor, on-site, energy.

Journal

Architectural Engineering and Design Management

APPENDIX I PROJECT TENDER ENQUIRY DOCUMENTS

The content below displays the basic characteristics of seven large-scale civil engineering and infrastructure projects and corresponding tender enquiry documents explored within research cycle five.

Key findings from the review of project 1 tender enquiry documents

Project Details	Key Findings
Project Name Project 1 **Client Type** Client A **Project Value** £140 million **Project Start Date** Start April 2014 **Project Description** New build large-scale rail depot located South England **Documents Reviewed** Document No. 1 Document No. 7	- The client expected 20% of their operational energy use to derive from renewable sources and aimed to benefit from substantial improvements to life cycle running costs; - The contractor planned to integrate a selection of renewables (e.g. photovoltaic panels, solar thermal panels, combined heat and power, ground source heat pump) to achieve client expectations. Emphasis towards renewables is in agreement with Buchanan and Honey (1994), Pries (2003), Kohler et al. (2006), DECC (2009b) and Liu et al. (2014); - No emphasis towards initial embodied impacts or demolition embodied impacts were identified by the client. Lack of emphasis towards initial embodied energy is in accordance with BIS (2010), RICS (2010) and Monahan and Powell (2011); - The client noted a minimum of a Very Good BREEAM 2011 rating for their project as a practical completion requirement. Emphasis towards BREEAM is in agreement with Energy Saving Trust (2009), Doran and Anderson (2011) and BREEAM (2014b); - The client proposed no minimum rating per individual BREEAM section (e.g. management, energy, materials); - The contractor highlighted a commitment to only procure high Green Guide rating materials (i.e. A or A+) and only use suppliers that have an ISO 14001 accreditation. Emphasis towards Green Guide is in agreement with Fieldson and Rai (2009), Halcrow Yolles (2010) and Anderson et al. (2011) whereby commitment towards ISO 14001 accreditation is in agreement with Biondi et al. (2000) and Nakamura et al. (2001); - The contractor highlighted that thermal insulation products used would have a low embodied impact relative to their thermal properties; - The contractor targeted reduced material phase impact with regards to external walls, windows, roof, upper floor slab, internal walls, and floor finishes construction packages in line with BREEAM requirements; - The contractor identified that all sub-contractors are required to use low energy plant and equipment. Emphasis towards low energy plant is in agreement with RICS (2008) and Ko (2010); - The profile of the contractor’s environmental manager had no reference to LCA awareness; - The client outlined that the environmental agenda of the project had a 2% weighting on the overall project tender submission in contrast to project planning and project management which were weighted as 28% and 18% respectively. Emphasis towards construction programme is in agreement with Anderson and Mills (2002) and Sodagar and Fieldson (2008); - No direct reference was made towards the use and benefit of an LCA by the client or contractor.

Key findings from the review of project 2 tender enquiry documents

Project Details	Key Findings
Project Name Project 2 **Client Type** Client A **Project Value** £105 million **Project Start Date** Start April 2014 **Project Description** New build large-scale train station, office building and fit out works located in South England **Documents Reviewed** Document No. 2 Document No. 4 Document No. 5 Document No. 6 Document No. 8	- The client presented a question to the contractor with regards to commitment towards procuring green materials (making a direct reference to low embodied energy). Emphasis towards low embodied energy materials is in agreement with Harris (1999), Chen et al. (2001), and Rai et al. (2011); - The contractor's response made no reference to embodied energy or LCA when providing good examples of material procurement within previous projects; - The client presented a question to the contractor with regards to energy consumption and monitoring commitment during construction; - The contractor's response highlighted a commitment towards on-site electrical energy metering, the electrical energy tariff, and project specific targets. Emphasis towards on-site energy metering is in agreement with Firth et al. (2008), BIS (2010) and Ko, 2010; - The contractor highlighted their commitment towards environmental value associated with their supply chain and materials selection. Emphasis towards supply chain improvements is in agreement with Bansal and Hunter, (2003), Bellesi et al. (2005) and Grolleau et al. (2007); - The contractor indicated that sub-contractors would be evaluated and selected against a detailed criteria including their sustainable development commitment; - The contractor emphasised the importance of measuring the performance of their sub-contractors; - The contractor highlighted their commitment towards using BIM to coordinate the design development and transfer of information. Emphasis towards BIM is in agreement with Vilkner et al. (2007), Goedert and Meadati (2008), Mah et al. (2010) and Wu et al., 2014; - The contractor indicated their design management approach will ensure an environmentally sustainable solution. Emphasis towards design is in agreement with Goggins et al. (2010), Halcrow Yolles (2010) and Rai et al. (2011); - The contractor detailed how the environmental agenda of the project would be satisfied through continual monitoring and corrective actions from weekly on-site inspections, review of BREEAM information, capture of EPI data, and multiple ISO 14001 compliance audits. Emphasis towards BREEAM is in agreement with Energy Saving Trust (2009), Doran and Anderson (2011) and BREEAM (2014b) whereas commitment towards ISO 14001 accreditation is in agreement with Biondi et al. (2000) and Nakamura et al. (2001); - The contractor made no commitment towards a LCA or consideration of initial embodied energy within their environmental plan; - The contractor acknowledged that all sub-contractors would be required to procure green materials and use low energy plant and equipment. Emphasis towards low energy plant is in agreement with RICS (2008) and Ko (2010); - The profile of the contractor's environmental manager had no reference to LCA awareness; - The contractor highlighted their commitment towards selecting locally sourced sub-contractors and materials. Emphasis towards local operatives and materials is in agreement with BRE (2003), Citherlet and Defaux (2007), Sodagar and Fieldson (2008); - Only two questions within the PQQ asked by the client were directed towards environmental matters.

Key findings from the review of project 3 tender enquiry documents

Project Details	Key Findings
Project Name Project 3 **Client Type** Client B **Project Value** £85 million **Project Start Date** Start June 2015 **Project Description** New build roadway (widening) and control centre located in South England **Documents Reviewed** Document No. 2 Document No. 3 Document No. 7 Document No. 11	- The client presented a question for the contractor to demonstrate how they would expect to deliver exemplar economic, environmental and social outcomes at programme and construction package level. Emphasis towards outcomes at a construction package level is in disagreement with Chen et al. (2001), Pitt et al. (2008) and Morton et al. (2011); - The contractor's response made reference to a commitment towards measuring the embodied carbon within key materials, although did not detail the method which would be used to achieve this. Emphasis towards measuring embodied impact without a standardised, validated method is in disagreement with Sodagar and Fieldson (2008), BIS (2010), Halcrow Yolles (2010) and Ko (2010); - The contractor's response emphasised that the construction manager will review in pre-construction the materials, technology and site accommodation needed to deliver works to identify ways to reduce embodied energy and carbon through various methods (e.g. share facilities and resources with other contractors, connect project offices to mains electricity supply, efficient use of plant and equipment, trailing new technologies, and setting targets and continually monitoring performance). Emphasis towards mains connection is in agreement with RICS (2008) and Ko (2010); - With regards to a question relating to managing financial risk, the contractor highlighted the use of life cycle costing plans to be developed and measured against capital expenditure parameters to provide best value options. Emphasis towards life cycle costing is in agreement with Leckner and Zmeureanu (2011); - With regards to a question relating to pre and on-site construction, the contractor emphasised their commitment towards prefabrication, off-line assembly and product standardisation across construction packages, and also whole life cycle performance requirements. Emphasis towards prefabrication is in agreement with Halcrow Yolles (2010); - The contractor highlighted during their response that they will promote the use of BIM at the core of all our activities and propose that a common strategy and unified processes should be established and applied across all work packages; - The contractor also highlighted that BIM will be used to improve and include quantity, cost, time and asset maintenance information into the model for a whole lifecycle solution. Emphasis towards BIM is in agreement with Vilkner et al. (2007), Goedert and Meadati (2008), Mah et al. (2010) and Wu et al., 2014; - The client emphasised their target towards zero environmental pollution incidents; - The client emphasised that sustainability was one of the key areas of the tender and contractors would be expected to deliver better services which have reduced environmental impacts and improved efficient processes; - The profile of the contractor's environmental manager had no reference to LCA awareness; - The contractor outlined their commitment towards using technologies that would reduce the embodied and operational carbon performance of the project. Emphasis towards use of technologies is in agreement with Hinnells (2008) and Sodagar and Fieldson (2008).

Key findings from the review of project 4 tender enquiry documents

Project Details	Key Findings
Project Name Project 4 **Client Type** Client C **Project Value** £115 million **Project Start Date** Start Mar 2015 **Project Description** New build large-scale rail track, bridge and utility diversion located within South England **Documents Reviewed** Document No. 2 Document No. 9	- The client outlined that the environmental agenda (including quality) of the project had a 30% weighting on the overall project tender submission whereas the experience, capacity and capability of the contractor was weighted as 50%. Emphasis towards the importance of an environmental agenda is in disagreement with Hale and Lachowicz (1998), Hertin et al. (2003), Heath and Gifford (2006) and Morton et al. (2011); - The client expected the contractor to have an ISO 14001 accreditation. Emphasis towards ISO 14001 accreditation is in agreement with Biondi et al. (2000) and Nakamura et al. (2001); - The client presented a question which highlighted their commitment towards embodied energy consideration and requested the contractor to expand on their experience and capability of measuring the embodied impact of their operations. Emphasis towards embodied energy consideration is in disagreement with Chen et al. (2001), Pitt et al. (2008) and Morton et al. (2011); - The contractor's response made reference to a commitment towards measuring the embodied carbon within key materials, although did not detail the method which would be used to achieve this. Emphasis to measure embodied impact without standardised, validated method is in agreement with Sodagar and Fieldson (2008), BIS (2010), Halcrow Yolles (2010) and Ko (2010); - The contractor's response acknowledged that accurately assessing the embodied impact of materials is a difficult task due to a lack of visibility throughout the entire supply chain. Emphasis towards the difficult in assessing embodied impacts is in agreement with Hernandez et al. (2008), BIS (2010), Halcrow Yolles (2010); - The contractor's response acknowledged that the biggest embodied impact is in the design where, when they are contracted to manage the design, they will promote the use of Green Guide. Emphasis towards Green Guide is in agreement with Fieldson and Rai (2009), Halcrow Yolles (2010) and Anderson et al. (2011); - The contractor's response also highlighted a commitment towards on-site electrical energy metering, the electrical energy tariff, and project specific targets. Emphasis towards on-site energy metering is in agreement with Firth et al. (2008), BIS (2010) and Ko (2010); - The client highlighted a Very Good CEEQUAL (The Civil Engineering Environmental Quality and Assessment Scheme) rating for their project as a practical completion requirement; - The contractor's response included examples of previous projects which have all achieved a Very Good or better rating; - The contractor acknowledged that all sub-contractors would be required to procure green materials and use low energy plant and equipment. Emphasis towards low energy plant is in agreement with RICS (2008) and Ko (2010); - The contractor highlighted key environmental risks of the project (heritage, ecology, noise, water, community engagement) overlooking energy and carbon considerations; - The contractor highlighted their commitment towards selecting locally sourced sub-contractors and materials. Emphasis towards local operatives and materials is in agreement with BRE (2003), Citherlet and Defaux (2007), Sodagar and Fieldson (2008); - The contractor highlighted their commitment towards procurement of sustainably sourced timber expecting suppliers to have the appropriate FSC (Forest Stewardship Council) or PEFC (Programme for the Endorsement of Forest Certification) accreditation. Emphasis towards timber use in agreement with Buchanan and Honey (1994).

Key findings from the review of project 5 tender enquiry documents

Project Details	Key Findings
Project Name Project 5 **Client Type** Client C **Project Value** £98 million **Project Start Date** Start April 2014 **Project Description** New build large-scale station, platform extension and accommodation building located within South England **Documents Reviewed** Document No. 1 Document No. 2 Document No. 10	- The client outlined that the environmental agenda (including health and safety and quality) of the project was deemed as a pass or fail criterion (i.e. minimum requirements had to be met before the remaining tender response was considered) whereas the price (i.e. cost) of the tender was weighted as 60%. Emphasis towards the importance of an environmental agenda is in disagreement with Hale and Lachowicz (1998), Hertin et al. (2003), Heath and Gifford (2006) and Morton et al. (2011); - The client supported alternative solutions which did not necessarily fall in line with the requirements of the original project scope but offered substantial benefits in terms of whole life cost and environmental performance; - The contractor's response included alternative solutions with supporting embodied carbon calculations to highlight potential savings from different methods of construction and design, although did not detail the method used or data source to achieve this. Emphasis to measure embodied impact without standardised, validated method is in agreement with Sodagar and Fieldson (2008), BIS (2010), Halcrow Yolles (2010) and Ko (2010); - The contractor highlighted their commitment towards procurement of sustainably sourced timber expecting suppliers to have the appropriate FSC (Forest Stewardship Council) or PEFC (Programme for the Endorsement of Forest Certification) accreditation. Emphasis towards timber use in agreement with Buchanan and Honey (1994); - The contractor emphasised the importance of the Environmental Management System (EMS) which was portrayed to help them demonstrate their environmental performance by minimising the negative impact of their operations, whilst maximising the potential for environmental improvement. Emphasis towards the EMS is in agreement with Biondi et al. (2000), Nakamura et al. (2001), Quazi et al. (2001) and Carbon Connect (2011); - The contractor emphasised their commitment towards reducing their footprint on the natural environment by encouraging sustainable design and construction at all levels. Emphasis towards carbon footprinting is in agreement with Sodagar and Fieldson (2009), Wiedmann (2009) and Doran and Anderson (2011); - The contractor highlighted their commitment towards using energy efficient on-site accommodation and low carbon concrete mixes during construction. Emphasis towards on-site accommodation is in agreement with Ko (2010) where commitment towards low carbon concrete mixes is in agreement with Goggins et al. (2010) and Habert and Roussel (2009).

Key findings from the review of project 6 tender enquiry documents

Project Details	Key Findings
Project Name Project 6 **Client Type** Client C **Project Value** £35 million **Project Start Date** Start Oct 2015 **Project Description** New build large-scale rail track, multiple structures and refurbishment of two stations located within South England **Documents Reviewed** Document No. 1 Document No. 2 Document No. 10	- The client proposed a question (i.e. example problem) with regards to understanding the carbon and energy associated with the design, on-site construction and during operation; - The contractor's response demonstrated commitment towards integrating carbon data (from the ICE material database, Defra Guide and manufacture literature) into the BIM model to enable embodied carbon estimating and forecasting to be undertaken during project development across the entire supply chain. Emphasis towards the data sources is in agreement with CDP (2009), IEMA (2010), Goggins et al. (2010), Carbon Connect (2011) and Rai et al. (2011); - The contractor highlighted their commitment towards implementing 5D BIM in order to bring an integrated approach to design and construction, utilising common data environments and other coordination tools. Emphasis towards BIM is in agreement with Vilkner et al. (2007), Goedert and Meadati (2008), Mah et al. (2010) and Wu et al., 2014; - The contractor demonstrated multiple examples of good environmental management practice (e.g. segregated waste management) from previous projects; - The contractor indicated they will use carbon footprinting to assess the design, material, and plant selection during project development. Emphasis towards carbon footprinting is in agreement with Sodagar and Fieldson (2009), Wiedmann (2009) and Doran and Anderson (2011); - The contractor noted that they would employ an energy champion who would be responsible for identifying energy saving measures. Emphasis towards individual responsibility is in agreement with Carbon Connect (2011); - The contractor highlighted they would measure fuel and electrical energy consumption during on-site construction and reduce the use of virgin materials during material selection. Emphasis towards on-site metering of energy is in agreement with Firth et al. (2008), Carbon Connect (2011) and Gill et al. (2011) whereas commitment to reduce virgin material use is in agreement with Chen et al. (2001), Habert and Roussel (2009), Goggins et al. (2010) and Cabeza et al. (2013).

Key findings from the review of project 7 tender enquiry documents

Project Details	Key Findings
Project Name Project 7 **Client Type** Client C **Project Value** £120 million **Project Start Date** Start Dec 2015 **Project Description** New build large-scale train station and rail track located within South England **Documents Reviewed** Document No. 1 Document No. 2 Document No. 10	- The client outlined that the environmental agenda of the project had a 5% weighting on the overall project tender submission in contrast to project planning and resources which were weighted as 35%. Emphasis towards construction programme is in agreement with Anderson and Mills (2002) and Sodagar and Fieldson (2008); - The client proposed a question whereby the contractor had to demonstrate a Sustainability Strategy which focused around whole life costing, reduction of embodied carbon, material efficiency, and social sustainability. Emphasis towards low embodied energy materials is in agreement with Harris (1999), Chen et al. (2001), and Rai et al. (2011); - The contractor's response highlighted their commitment towards whole life cost modelling and providing benchmark information on energy, CO_2, water, waste re-cycling and other sustainability indicators. Emphasis towards benchmarking in agreement with Sodagar and Fieldson (2008), BIS (2010) and Goggins et al. (2010); - The contractor's response emphasised the use of their BIM strategy in order to understand the data needs of subsequent users throughout the infrastructure life cycle. Emphasis towards BIM is in agreement with Vilkner et al. (2007), Goedert and Meadati (2008), Mah et al. (2010) and Wu et al., 2014; - The contractor highlighted their commitment towards selecting locally sourced sub-contractors and materials. Emphasis towards local operatives and materials is in agreement with BRE (2003), Citherlet and Defaux (2007), Sodagar and Fieldson (2008); - The contractor outlined that the project embodied carbon and GHG emissions will be reduced through design workshops, reuse of the existing structure (where applicable), use of the rail networks to transport materials, use of recycled materials and concrete with low carbon mixes, and use innovative low carbon technologies. Emphasis towards recycled materials is in agreement with Harris (1999), Chen et al. (2001), and Rai et al. (2011); - The contractor highlighted their commitment towards procurement of sustainably sourced timber expecting suppliers to have the appropriate FSC (Forest Stewardship Council) or PEFC (Programme for the Endorsement of Forest Certification) accreditation. Emphasis towards timber use in agreement with Buchanan and Honey (1994); - The client highlighted a Very Good CEEQUAL (The Civil Engineering Environmental Quality and Assessment Scheme) rating for their project as a practical completion requirement; - The contractor's response included examples of previous projects which have all achieved a Very Good or better rating for CEEQUAL projects.

APPENDIX J PRACTICAL FRAMEWORK

The content below provides instructions for contractors to support the use of the developed practical framework from this research project within future construction projects and research.

FRAMEWORK INSTRUCTIONS

Overview

The framework is designed to provide contractors with a practical approach for initial embodied energy assessment which can help highlight opportunities to increase efficiency. The framework is based upon the use of current practices typically employed by a contractor during the construction phase of a project. The framework comprises of five key sections (principles, indicators, structure, equations and alignment) and is managed through the use of multiple Microsoft Excel spreadsheets in order to capture and assess initial embodied energy consumption.

Key Sections

The table below summarises the purpose and content of each key section.

Key Sections of the Framework	Purpose and Content
Principles Outlines how data would be explored	- Primary data captured from current practices for material, transportation and construction phase energy; - Secondary source data (ICE material database and Defra Guide) required for coefficient values for material, transportation and construction phase energy.
Indicators Outlines how data would be captured System Boundaries	- Organised in terms of project resources used across the three project life cycle phases; - Material phase: characteristics (type, no., m2, m3, tonne); - Transportation phase (materials): distance travelled (miles, km); vehicle use (type, no.); vehicle fuel used (petrol, diesel, etc.); vehicle fuel consumption (litres, kWh); vehicle load capacity (tonne, m^3); proportion of load (%); - Transportation phase (plant and equipment): distance travelled (miles, km); vehicle use (type, no.); vehicle fuel used (petrol, diesel, etc.); vehicle fuel consumption (litres, kWh); vehicle load capacity (tonne, m^3); proportion of load (%); - Transportation phase (operatives): distance travelled (miles, km); vehicle use (type, no.); vehicle fuel used (petrol, diesel, etc.); vehicle fuel consumption (litres, kWh); vehicle load capacity (tonne, m^3); proportion of load (%); - Construction phase: materials needed (type, no.); operatives needed (type, no.); plant needed (type, no.); plant duration of use (hrs, days); plant fuel type (petrol, diesel, etc.); plant fuel consumed (litres, kWh); plant power rating (v, a, watts);
Structure Outlines how data would be organised	- Designed to facilitate the capture and assessment of data via a three-tier structure; - Displays the relationship between each project resource (i.e. material, plant and equipment, and operatives) and their impact relative to each project life cycle phase.
Equations Outlines how data would be assessed Calculation Method	- Developed to assess captured data and provide the link between the indicators and structure; - Assigns data to specific life cycle phases (material, transportation and construction), construction packages and construction activities to produce a holistic overview.
Alignment Outlines what and how data would be sourced Data Source	- Outlines what and how data would be sourced; - Bill of Quantities captured information on MAT type and quantity per sub-contractor; - Design Drawings captured information on MAT specification, detail and measurement per sub-contractor; - Plant Register captured information on P&E type and quantity per sub-contractor; - Environmental Performance Indicator (EPI) procedure captured information (e.g. monthly) on fuel type and quantity per sub-contractor; - Sign-in Sheets (Forms ‘A’, ‘B’ and ‘C’) captured information (e.g. daily, weekly or monthly) on transportation type, distance travelled, and fuel type for MAT, P&E, OPP movements per sub-contractor; - Programme of Works (PoW) captured information (e.g. daily, weekly or monthly) on construction package and activity duration.

Data Management

The table below displays the content of each Microsoft Excel spreadsheet required to create and manage the data requirements within the framework.

Name[a]	Spreadsheet Details and Data Source[a]
PoW	Spreadsheet displays the colour coded PoW which highlights sub-contractor responsibility. This information is extracted from the project's original PoW. Two spreadsheets (high-level which is basic and low-level which is detailed) should be created.
MAT	Spreadsheet displays list of all materials linked to each construction activity, package and sub-contractor. This information is extracted from the project's original BoQ and Design Drawings.
TRAN Materials	Spreadsheet displays list of all materials movements (to and from site) linked to each construction activity, package and sub-contractor. This information is extracted from the project's original BoQ and FORM 'A' data.
TRAN Plant and Equipment	Spreadsheet displays list of all plant and equipment movements (to and from site) linked to each construction activity, package and sub-contractor. This information is extracted from the project's original Plant Register and Forms 'A' and 'C' data.
TRAN Operatives	Spreadsheet displays list of all operative movements (to and from site) linked to each construction activity, package and sub-contractor. This information is extracted from the project's Forms 'B' and 'C' data.
CON	Spreadsheet displays list of all energy consumed (e.g. red diesel, electrical) linked to each construction activity, package and sub-contractor. This information is extracted from the project's Forms 'B' and 'C' data.

[a] Name: PoW, Programme of Works; BoQ, Bill of Quantities; MAT, material phase; TRAN, transportation phase; CON, construction phase

Capturing and Assessing Data

The remaining content outlines how data would be captured and assessed via the use of the framework. The content is split into six headings, all of which is interconnected within the final diagram:

[1] Bill of Quantities (BoQ) and Design Drawings (Material phase data)
[2] Form 'B' (Transportation of operatives)
[3] Form 'A' (Transportation of material and plant and equipment)
[4] Form 'C' (Construction phase data)
[5] Environmental Performance Indicator (EPI) Procedure (Construction phase data)
[6] Programme of Works (PoW)

Notably the selection of headings reflects the sequence of captured data throughout a project life cycle in order to successfully link data per construction activity, package or sub-contractor.

[1] Bill of Quantities and Design Drawings (Material phase data)

The diagram below displays a template of data which is required to assess the material phase energy consumption for each construction activity, package and sub-contractor. The BoQ and Design Drawings would provide the necessary characteristic details on materials. Data is required to be captured at the beginning of a project and updated to reflect changes in planned activities and when additional construction packages have been awarded. Data (i.e. material characteristics) would be correlated against coefficient values within the Defra Guide to produce actual embodied energy values.

Material Phase Data

Data Source[a]				ICE	BoQ		BoQ	BoQ			ICE	ICE					BoQ		
Calculation Method						A x B		B x D	C x D	A x E			C x H	C x J	F x H (or G x H)[e]	G x J		M / P	N / P
Calculation Ref.				A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R
Calc' Units[b c]				1	2	3	4	5	6	6	7	8	9	10	11	12	4	9	10
Sub-Contractor Name	**Package Name**	**Activity Name**	**Material Name**	Density	Thickness	Mass	Area	Volume	Total Mass [Area]	Total Mass [Vol]	EE per Mass	EC per Mass	EE per $1m^2$	EC per $1m^2$	EE for Whole Build	EC for Whole Build	Total Build Area	EE per $1m^2$ [Whole]	EC per $1m^2$ [Whole]
Sub-contractor No.5	Package No. 5	Activity No. 5A	Material Name	kg/m3	m	kg/m2	m2	m3	kg	kg	MJ/kg	kgCO2e/kg	MJ/m2	kgCO2e/m2	MJ	kgCO2e	m2	MJ/m2	kgCO2e/m2
Sub-contractor No.5	Package No. 5	Activity No. 5B	Material Name	kg/m3	m	kg/m2	m2	m3	kg	kg	MJ/kg	kgCO2e/kg	MJ/m2	kgCO2e/m2	MJ	kgCO2e	m2	MJ/m2	kgCO2e/m2
Sub-contractor No.5	Package No. 5	Activity No. 5C	Material Name	kg/m3	m	kg/m2	m2	m3	kg	kg	MJ/kg	kgCO2e/kg	MJ/m2	kgCO2e/m2	MJ	kgCO2e	m2	MJ/m2	kgCO2e/m2
Sub-contractor No.6	Package No. 6	Activity No. 6A	Material Name	kg/m3	m	kg/m2	m2	m3	kg	kg	MJ/kg	kgCO2e/kg	MJ/m2	kgCO2e/m2	MJ	kgCO2e	m2	MJ/m2	kgCO2e/m2
Sub-contractor No.6	Package No. 6	Activity No. 6B	Material Name	kg/m3	m	kg/m2	m2	m3	kg	kg	MJ/kg	kgCO2e/kg	MJ/m2	kgCO2e/m2	MJ	kgCO2e	m2	MJ/m2	kgCO2e/m2
Sub-contractor No.6	Package No. 6	Activity No. 6C	Material Name	kg/m3	m	kg/m2	m2	m3	kg	kg	MJ/kg	kgCO2e/kg	MJ/m2	kgCO2e/m2	MJ	kgCO2e	m2	MJ/m2	kgCO2e/m2
Sub-contractor No.6	Package No. 6	Activity No. 6D	Material Name	kg/m3	m	kg/m2	m2	m3	kg	kg	MJ/kg	kgCO2e/kg	MJ/m2	kgCO2e/m2	MJ	kgCO2e	m2	MJ/m2	kgCO2e/m2

[2] Form 'B' (Transportation of operatives)

In terms of Form 'B', the diagram below displays a template of data which is required to capture operative movements per sub-contractor. Data is required to be captured throughout the entire project duration. Data (i.e. fuel use and vehicle type) would be correlated against coefficient values within the Defra Guide to produce actual embodied energy values.

Transportation Phase Data (Operatives)

Induction Number	**Date**	**Operative Full Name**	**Operative Signature**	**Sub-contactor Name**	**Time In**	**Time Out**	**Vehicle Type**	**Registration No.**	**Fuel Type**	**No. Passengers in Vehicle** (not driver)	**Travel From** (city OR postcode)	**Distance Travelled** (miles)	**Total Distance** (to and from site)	**Convert** (miles to km)	**Coefficient Value for V Type** (from Defra Guide)	**Total energy Consumption**
No.1	Date	Operative Name	Note	Sub-contractor No.5	Time	Time	Description	Note	Type	No.	Location	Distance	Value	Value	Value	Value
No.2	Date	Operative Name	Note	Sub-contractor No.5	Time	Time	Description	Note	Type	No.	Location	Distance	Value	Value	Value	Value
No.3	Date	Operative Name	Note	Sub-contractor No.5	Time	Time	Description	Note	Type	No.	Location	Distance	Value	Value	Value	Value
No.4	Date	Operative Name	Note	Sub-contractor No.5	Time	Time	Description	Note	Type	No.	Location	Distance	Value	Value	Value	Value
No.5	Date	Operative Name	Note	Sub-contractor No.5	Time	Time	Description	Note	Type	No.	Location	Distance	Value	Value	Value	Value

[2] Form 'A' (Transportation of materials and plant and equipment)

Form 'B' would reflect material and plant and equipment transportation data. In terms of material movements, the diagram below displays a template of data which is required to be captured to correlate material data to sub-contractors. Data is required to be captured throughout the entire project duration. Data (i.e. fuel use and vehicle type) would be correlated against coefficient values within the Defra Guide to produce actual embodied energy values.

Transportation Phase Data (Materials)

Date	**Delivery OR Collection**	**Delivery Driver Name**	**Delivery Company Name**	**Main Delivery Item**(s) (if PLANT specify model)	**Intended Recipient Name** (company OR individual)	**Driver Signature**	**Time In**	**Time Out**	**Vehicle Type**	**Registration No.**	**Fuel Type**	**No. Passengers in Vehicle** (not driver)	**Travel From** (city OR postcode)	**Distance Travelled** (miles)	**Onward Travel Distance** (miles)	**Vehicle Load Capacity** (tonne OR m3)	**Proportion of Load** (% taken-up by delivery item)	**Total Distance** (to and from site)	**Convert** (miles to km)	**Coefficient Value for V Type** (from Defra Guide)
Date	Note	Name	Name	Material Name	Sub-contractor No.5	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value
Date	Note	Name	Name	Material Name	Sub-contractor No.5	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value
Date	Note	Name	Name	Material Name	Sub-contractor No.5	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value
Date	Note	Name	Name	Material Name	Sub-contractor No.6	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value
Date	Note	Name	Name	Material Name	Sub-contractor No.6	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value
Date	Note	Name	Name	Material Name	Sub-contractor No.6	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value
Date	Note	Name	Name	Material Name	Sub-contractor No.6	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value

In terms of plant and equipment movements, the diagram below displays a template of data which is required to be captured to correlate plant and equipment data to sub-contractors. Data is required to be captured throughout the project duration. Data (i.e. fuel use and vehicle type) would be correlated against coefficient values within the Defra Guide to produce actual embodied energy values. The Plant Register can provide additional validation of data to ensure all items of plant and equipment have been accounted for per construction activity during a specific interval (i.e. when an item of plant has arrived or left site).

Transportation Phase Data (Plant and Equipment)

Date	Delivery OR Collection	Delivery Driver Name	Delivery Company Name	Main Delivery Item (s) (if PLANT specify model)	Intended Recipient Name (company OR individual)	Driver Signature	Time In	Time Out	Vehicle Type	Registration No.	Fuel Type	No. Passengers in Vehicle (not driver)	Travel From (city OR postcode)	Distance Travelled (miles)	Onward Travel Distance (miles)	Vehicle Load Capacity (tonne OR m3)	Proportion of Load (% taken-up by delivery item)	Total Distance (to and from site)	Convert (miles to km)	Coefficient Value for V Type (from Defra Guide)	Total energy Consumption
Date	Note	Name	Name	Plant Name	Sub-contractor No.5	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value	Value
Date	Note	Name	Name	Plant Name	Sub-contractor No.5	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value	Value
Date	Note	Name	Name	Plant Name	Sub-contractor No.5	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value	Value
Date	Note	Name	Name	Plant Name	Sub-contractor No.6	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value	Value
Date	Note	Name	Name	Plant Name	Sub-contractor No.6	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value	Value
Date	Note	Name	Name	Plant Name	Sub-contractor No.6	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value	Value
Date	Note	Name	Name	Plant Name	Sub-contractor No.6	Note	Time	Time	Description	Note	Type	No.	Location	Distance	Distance	Size	Percentage	Value	Value	Value	Value

[4] Form 'C' (Construction phase data)

In terms of Form 'C', the diagram below displays a template of data which is required to link all transportation and construction phase data per construction activity. Data is required to be captured at the beginning of the project and updated to reflect changes in planned activities and when additional construction packages have been awarded. The Plant Register can provide additional validation of data to ensure all items of plant and equipment have been accounted for per construction activity during a specific interval (i.e. when an item of plant has arrived or left site).

Construction Phase Data (Link to Construction Activities)

Date	Sub-contactor Name	Package Name	Activity Name	Induction Number	Operative Full Name	Operative Occupation	Plant and Equipment Required
Date	Sub-contractor No.5	Package No.5	Activity No. 5A	No.1	Operative Name	Description	Plant Name
Date	Sub-contractor No.5	Package No.5	Activity No. 5A	No.2	Operative Name	Description	Plant Name
Date	Sub-contractor No.5	Package No.5	Activity No. 5A	No.3	Operative Name	Description	Plant Name
Date	Sub-contractor No.5	Package No.5	Activity No. 5A	No.4	Operative Name	Description	Plant Name
Date	Sub-contractor No.5	Package No.5	Activity No. 5A	No.5	Operative Name	Description	Plant Name
Date	Sub-contractor No.5	Package No.5	Activity No. 5A	No.6	Operative Name	Description	Plant Name

<u>[5] Form ‘C’ (Construction Environmental Performance Indicator (EPI) Procedure (Construction phase data)</u>

In terms of the EPI procedure, the diagram below displays a template of data which is required to assess the construction phase energy consumption for each construction package and sub-contractor. Data is required to be captured weekly and displayed in line with the content of the PoW to ensure a full scope of data per sub-contractor. Fuel delivery ticket information (i.e. litres of fuel used) or electrical meter readings would be correlated again coefficient values within the Defra Guide to produce actual embodied energy values.

Construction Phase Data

		Month 1				Month 2				Month 3					Month 4				Month 5					Month 6				Month 7			
Package Name	**Sub-Contractor Name**	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23	Week 24	Week 25	Week 26	Week 27	Week 28	Week 29	Week 30
Package No 1	Sub-contractor No.1																														
Package No 2	Sub-contractor No.2																														
Package No 3	Sub-contractor No.3																														
Package No 4	Sub-contractor No.4																														
Package No 5	Sub-contractor No.5								GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ	GJ				
Package No 6	Sub-contractor No.6																														
	Total	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value
	Running Total	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value

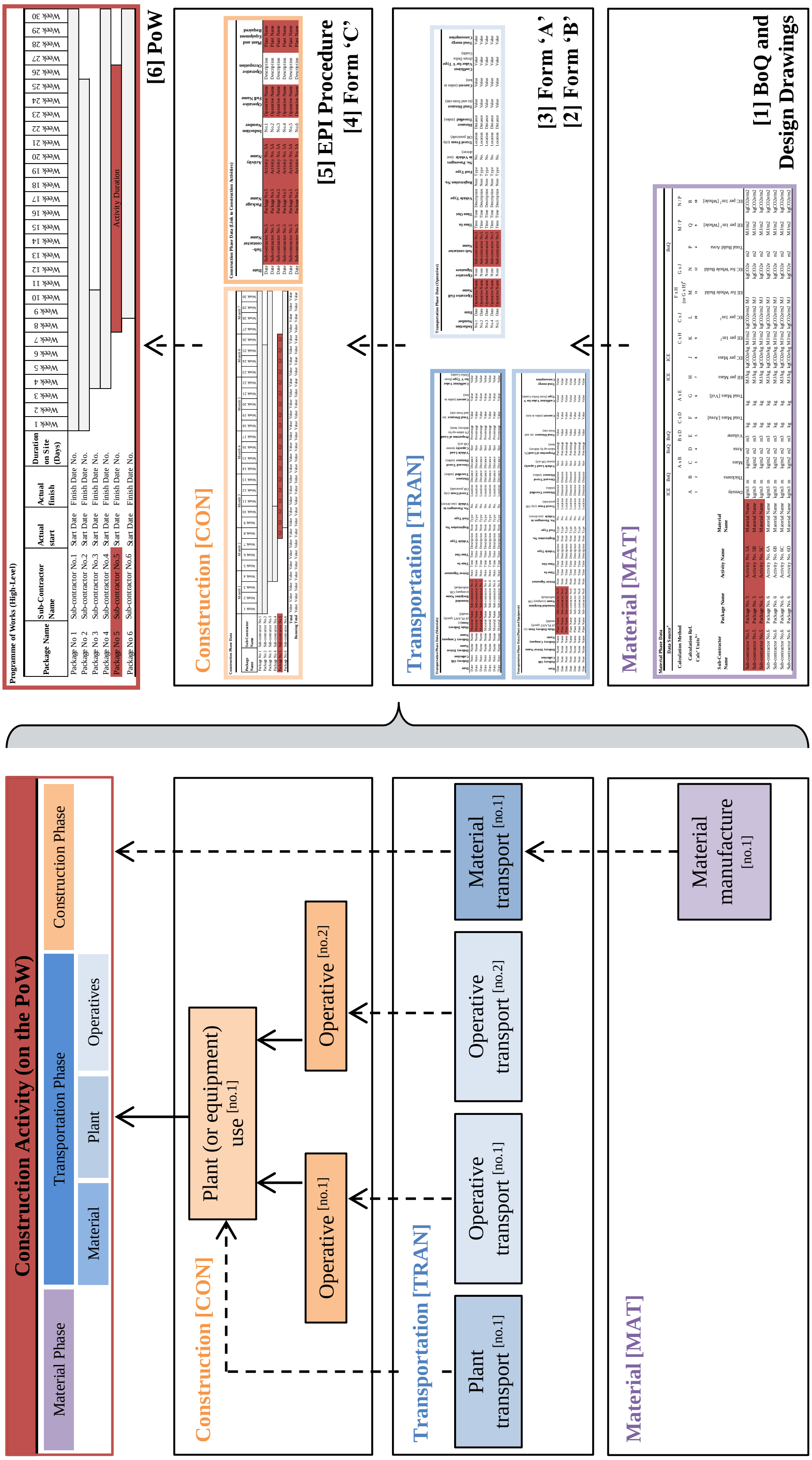
<u>[6] Programme of Works (PoW)</u>

The PoW provides the link between construction activity, package and sub-contractor data. The diagram below displays a template of data which is required to support the entire framework structure. Data is required to be captured at the beginning of a project and updated to reflect changes in planned activities and when additional construction packages have been awarded.

Programme of Works (High-Level)

Package Name	**Sub-Contractor Name**	**Actual start**	**Actual finish**	**Duration on Site (Days)**	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18	Week 19	Week 20	Week 21	Week 22	Week 23	Week 24	Week 25	Week 26	Week 27	Week 28	Week 29	Week 30
Package No 1	Sub-contractor No.1	Start Date	Finish Date	No.																														
Package No 2	Sub-contractor No.2	Start Date	Finish Date	No.																														
Package No 3	Sub-contractor No.3	Start Date	Finish Date	No.																														
Package No 4	Sub-contractor No.4	Start Date	Finish Date	No.																														
Package No 5	Sub-contractor No.5	Start Date	Finish Date	No.																	Activity Duration													
Package No 6	Sub-contractor No.6	Start Date	Finish Date	No.																														

The final diagram displays how data is structure per construction activity (left side) and what is the relationship between primary data sources (right side) within the framework. The highlighted red data shows how data would be connected across different sources to assess the initial embodied energy consumption per construction activity.


Construction Activity (on the PoW)
Material Phase
Transportation Phase
Construction Phase
Material
Plant
Operatives
Construction [CON]
Plant (or equipment) use [no.1]
Operative [no.1]
Operative [no.2]
Transportation [TRAN]
Plant transport [no.1]
Operative transport [no.1]
Operative transport [no.2]
Material transport [no.1]
Material [MAT]
Material manufacture [no.1]
Programme of Works (High-Level)
[6] PoW
[5] EPI Procedure
[4] Form 'C'
[3] Form 'A'
[2] Form 'B'
[1] BoQ and Design Drawings