



Citation for published version:

Davies, PJ, Emmitt, S & Firth, SK 2015, 'Delivering improved initial embodied energy efficiency during construction', *Sustainable Cities and Society*, vol. 14, pp. 267-279. <https://doi.org/10.1016/j.scs.2014.09.010>

DOI:

[10.1016/j.scs.2014.09.010](https://doi.org/10.1016/j.scs.2014.09.010)

Publication date:

2015

Document Version

Peer reviewed version

[Link to publication](#)

Published version available via: <http://dx.doi.org/10.1016/j.scs.2014.09.010>

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**DELIVERING IMPROVED INITIAL EMBODIED ENERGY EFFICIENCY
DURING CONSTRUCTION**

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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.

Key words: initial embodied energy, efficiency, material, transportation, industrial warehouse, construction, contractor.

1.0 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, & Nasser, 2010; Vilkner, Wodzicki, Hatfield, & Scarangelo, 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 equipped 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, & Nasser, 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).

2.0 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.

<Insert TABLE 1>

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.

<Insert TABLE 2>

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:

$$EE_{\text{Initial}} = \sum_{k=1}^{N_j} \left(\sum_{j=1}^P \left(\sum_{i=1}^3 EE_{ijk} \right) \right) \quad (1)$$

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 N_j 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.

<Insert FIGURE 1>

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.

<Insert TABLE 3>

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).

3.0 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.

<Insert TABLE 4>

<Insert TABLE 5>

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).

<Insert TABLE 6>

<Insert TABLE 7>

<Insert TABLE 8>

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.

<Insert TABLE 9>

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.

<Insert TABLE 10>

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.

<Insert TABLE 11>

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.

<Insert TABLE 12>

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 (m^3) and density (kg/m^3) 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.

5 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.

Acknowledgements

The authors wish to acknowledge the research funding 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.

References

- [1] Adalberth, K. (1997). Energy use during the Life Cycle of Buildings: a Method. *Building and Environment*, 32(4), 317-320.
- [2] Anderson, J., Mills, K. (2002). BRE IP9/02 Part 1 Refurbishment or Redevelopment of Office Buildings? *Sustainability Comparisons*. BRE. Available: ISBN 1-86081-568-5.
- [3] BICS. (2006). Life Expectancy of Building Components, Second Edition. London: Connelly-Manton Printing Ltd.

- [4] BIS. (2010). Low Carbon Construction, Innovation & Growth Team, Final Report. London: BIS.
- [5] Blengini, G., Di Carol, T. (2010). The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings*, 42, 869-880.
- [6] BRE (2011). BREEAM New Construction: Non-Domestic Buildings Technical Manual SD5073-2.0:2011. BRE. Available at: <http://goo.gl/ssq21o>.
- [7] BRE. (2003). Construction site transportation the next big thing. Watford: BRE.
- [8] BSRIA. (2011). Embodied Carbon The Inventory of Carbon and Energy. London: BSRIA.
- [9] Buchanan, A., Honey, B. (1994). Energy and carbon dioxide implications of building construction. *Energy and Buildings*, 20, 205-217.
- [10] Cabeza, L., Barreneche, C., Miro, L., Morera, J., Bartoli, E., Fernandez, A. (2013). Low carbon and low embodied energy materials in buildings: A review. *Renewable and Sustainable Energy Reviews*, 23, 536-542.
- [11] Cabeza, L., Rincon, L., Vilarino, V., Perez, G., Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 29, 394-416.
- [12] Carbon Connect. (2011). Energy efficiency the untapped business opportunity. London: Carbon Connect.
- [13] Chau, C., Yik, F., Hui, W., Liu, H., Yu, H. (2007). Environmental impacts of building materials and building services components for commercial buildings in Hong Kong. *Journal of Cleaner Production*, 15(18), 1840-1851.
- [14] Chen, T., Burnett, J., Chau, C. (2001). Analysis of embodied energy use in the residential building of Hong Kong. *Energy*, 26, 232-340.
- [15] Citherlet, S., Defaux, T. (2007). Energy and environmental comparison of three variants of a family house during its whole life span. *Building and Environment*, 42, 591-598.

- [16] Cole, R. (1999). Energy and greenhouse gas emissions associated with the construction of alternative structural systems. *Building and Environment*, 34(3), 335-348.
- [17] Cole, R., Kernan, P. (1996). Life-cycle energy use in office buildings. *Building and Environment*, 31(4), 307-317.
- [18] Dakwale, V., Raglegaonkar, R., Mandavgane, S. (2011). Improving environmental performance of building through increased energy efficiency: A review. *Sustainable Cities and Society*, 1, 211-218.
- [19] 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.
- [20] 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.
- [21] 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.
- [22] de Wilde, P. (2014). The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction*, 41, 40-49.
- [23] DECC. (2009a). The UK Low Carbon Transition Plan, National strategy for climate change and energy. London: DECC.
- [24] DECC. (2009b). Alternative policies for promoting low carbon innovation. London: Frontier Economics.
- [25] DECC. (2012). Decarbonisation and Carbon Capture and Storage Progress. London: DECC.
- [26] DEFRA. (2012). Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. *DEFRA*. Available: <http://goo.gl/dU8s4M>.

- [27] DIAG. (2011). Building Performance Directive Implementation Advisory Group. *DIAG*. Available: <http://www.diag.org.uk/>.
- [28] Ding, G., Forsythe, P. (2013). Sustainable construction: life cycle energy analysis of construction on sloping sites for residential buildings. *Construction Management and Economics*, 31(3), 254-265.
- [29] Dixit, M., Fernandez-Solis, J., Lavy, S., Culp, C. (2010). Identification of parameters for embodied energy measurement: A literature review. *Energy and Buildings*, 42, 1238-1247.
- [30] Dixit, M., Fernandez-Solis, J., Lavy, S., Culp, S. (2012). Need for an embodied energy measurement protocol for buildings: A review paper. *Renewable and Sustainable Energy Reviews*, 16, 3730-3743.
- [31] Doran, D., Anderson, J. (2011). Carbon Footprinting and Labelling of Construction Products, Information Paper IP 5/11. *BRE*. Available: ISBN 978-1-84806-190-3
- [32] ERA. (2014). Sustainability in the Rental Industry. *ERA*. Available at: <http://goo.gl/gu6Pgs>.
- [33] Fay, R., Treloar, G., Raniga, U. (2000). Life-cycle analysis of buildings: a case study. *Building Research & Information*, 28(1), 31-41.
- [34] Fieldson, R., Rai, D. (2009). An assessment of carbon emissions from retail fit-out in the United Kingdom. *Journal of Retail & Leisure Property*, 8, 243-258.
- [35] Firth, S.K., Lomas, K., Wright, A., Wall, R. (2008). Identifying trends in the use of domestic appliances from household electricity consumption measurements. *Energy and Buildings*, 40, 926-936.
- [36] Gill, Z., Tierney, M., Pegg, I., Allan, N. (2011). Measured energy and water performance of an aspiring low energy/carbon affordable housing site in the UK. *Energy and Buildings*, 43, 117-125.

- [37] Goedert, J., Meadati, P. (2008). Integrating construction process documentation into building information modelling. *Journal of Construction Engineering and Management*, 134(7), 509-516.
- [38] Goggins, J., Keane, T., Kelly, A. (2010). The assessment of embodied energy in typical reinforced concrete building structures in Ireland. *Energy and Buildings*, 42, 735-744.
- [39] Gustavsson, L., Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings*, 42, 210-220.
- [40] Gustavsson, L., Joelsson, A., Sathre, R. (2010). Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. *Energy and Buildings*, 42, 230-242.
- [41] Habert, G., Roussel, N. (2009). Study of two concrete mix-design strategies to reach carbon mitigation objectives. *Cement and Concrete Composites*, 31, 397-402.
- [42] Halcrow Yolles. (2010). Embodied Carbon Sustainable Offices: a supplementary report: Swindon: Halcrow Yolles.
- [43] Hamilton-MacLaren, F., Loveday, D., Mourshed, M. (2009). The calculation of embodied energy in new build UK housing. *Proceedings of the 25th Annual ARCOM Conference*, September 2009, Nottingham.
- [44] Harris, D. (1998). A quantitative approach to the assessment of the environmental impact of building materials. *Building and Environment*, 34, 751-758.
- [45] HM Treasury. (2013). Infrastructure Carbon Review. London: HM Treasury.
- [46] Iddon, C., Firth, S.K. (2013). Embodied and operational energy for new-build housing: A case study of construction methods in the UK. *Energy and Buildings*, 67, 479-488.
- [47] Karimpour, M., Belusko, M., Xing, K., Bruno, F. (2014). Minimising the life cycle energy of buildings: Review and analysis. *Building and Environment*, 73, 106-114.

- [48] Ko, J. (2010). Carbon: Reducing the footprint of the construction process. London: Construction Products Association.
- [49] Kofoworola, O., Gheewala, S. (2009). Life cycle energy assessment of a typical office building in Thailand. *Energy and Buildings*, 41, 1076-1083.
- [50] Langston, Y., Langston, C. (2008). Reliability of building embodied energy modelling: an analysis of 30 Melbourne case studies. *Construction Management and Economics*, 26(2), 147-160.
- [51] Legislation. (2008). Climate Change Act. *Legislation*. Available: <http://goo.gl/nhOaB3>.
- [52] Li, X., Zhu, Y., Zhang, Z. (2010). An LCA-based environment impact assessment model for construction processes. *Building and Environment*, 45, 766-775.
- [53] Mah, D., Manrique, J., Yu, H., Al-Hussein, M., Nasser, R. (2010). House construction CO₂ footprint quantification: a BIM approach. *Construction Innovation*, 11(2), 161-178.
- [54] Menezes, A., Cripps, A., Bouchlaghem, D., Buswell, R. (2011). Predicted vs actual energy performance of non-domestic buildings. *Third International Conference of Applied Energy*, 16-18 May, Italy.
- [55] Menezes, A., Nkonge, N., Cripps, A., Bouchlaghem, D., Buswell, R. (2012). Review of Benchmarks for Small Power Consumption in Office Buildings. *CIBSE*. Available at: <http://goo.gl/FhXHIQ>.
- [56] Monahan, J., Powell, J. (2011). An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework. *Energy and Buildings*, 43, 179-88.
- [57] Optis, M., Wild, P. (2010). Inadequate documentation in published life cycle energy reports on buildings. *The International Journal of Life Cycle Assessment*, 15(7), 644-651.

- [58] Pajchrowski, G., Noskowiak, A., Lewandowska, A., Strykowski, W. (2014). Materials composition or energy characteristic – What is more important in environmental life cycle of buildings? *Building and Environment*, 72, 15-27.
- [59] Rai, D., Sodagar, B., Fieldson, R., Hu, X. (2011). Assessment of CO2 emissions reduction in a distribution warehouse. *Energy*, 36, 2271-77.
- [60] RICS. (2010). Redefining Zero Carbon Profiling as a Solution to Whole Life Cycle Carbon Emission Measurement in Buildings. London: RICS.
- [61] RICS. (2012). Methodology to calculate embodied carbon of materials, RICS Information Paper. Coventry: RICS.
- [62] Scheuer, C., Keoleian, G., Reppe, P. (2003). Life cycle energy and environmental performance of a new university building: modelling challenges and design implications. *Energy and Buildings*, 35(10), 1049-1064.
- [63] Sodagar, B., Fieldson, R. (2008). Towards a sustainable construction practice. *Construction Information Quarterly*, 10(3), 101-108.
- [64] Srinivasan, R., Ingwersen, W., Trucco, C., Ries, R., Campbell, D. (2014). Comparison of energy-based indicators used in life cycle assessment tools for buildings. *Building and Environment*, 79, 138-151.
- [65] Takano, A., Winter, S., Hughes, M., Linkosalmi, L. (2014). Comparison of life cycle assessment databases: A case study on building assessment. *Building and Environment*, 79, 20-30.
- [66] Tassou, S., Hadawey, Y., Marriott, D. (2011). Energy consumption and conservation in food retailing. *Applied Thermal Engineering*, 31, 147-156.
- [67] The Carbon Trust. (2009). Building the future today – transforming the economic and carbon performance of the buildings we work in. London: The Carbon Trust.
- [68] Treloar, G., Love, P., Holt, G. (2001). Using national input-output data for embodied energy analysis of individual residential buildings. *Construction Management and Economics*, 19(1), 49-61.

- [69] Treloar, G., Love, P., Iyer-Raniga, O. (2000). A hybrid life cycle assessment method for construction. *Construction Management and Economics*, 18(1), 5-9.
- [70] Treloar, G., McCoubrie, A., Love, P., Tyer-Raniga, U. (1999). Embodied energy analysis of fixtures, fittings and furniture in office buildings. *Facilities*, 17(11), 403-409.
- [71] UK-GBC. (2012). Navigating sustainability in the building environment, Report from the UK-GBC Green Building Guidance Task Group. London: UK Green Building Council.
- [72] Van Ooteghem, K., Xu, L. (2012). The life-cycle assessment of a single-storey retail building in Canada. *Building and Environment*, 49, 212-226.
- [73] Vilknor, G., Wodzicki, C., Hatfield, E., Scarangelo, T. (2007). Integrated process in structural engineering. *New Horizons and Better Practices*, 1, 1-10.
- [74] Williams, D., Elghali, L., Wheeler, R., France, C. (2011). Climate change influence on building lifecycle greenhouse gas emissions: Case study on a UK mixed-use development. *Energy and Buildings*, 48, 112-126.

Figure Captions

Framework structure for capturing project life cycle data per construction activity (after Davies et al., 2014).