CHALLENGES FOR CAPTURING AND ASSESSING INITIAL EMBODIED ENERGY: A CONTRACTOR'S PERSPECTIVE

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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.

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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.

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).

<Insert FIGURE 1>

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).

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).

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).

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.

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).

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.

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).

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.

Method

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 °C), chilled (5 °C) and frozen (-23°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); 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.

<Insert TABLE 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.

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.

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).

<Insert TABLE 2>

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.

<Insert FIGURE 2>

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:

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

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:

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

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:

$$EE_{CON} = \sum_{l=1}^{p} EE_{Fuel,l} \tag{3}$$

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:

$$EE_{Initial} = EE_{MAT} + EE_{TRAN} + EE_{CON} \tag{4}$$

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

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.

<Insert TABLE 3>

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 (10^6) or GJ (10^9) and embodied carbon in terms of kilograms of carbon dioxide equivalent ($kgCO_2e$) whereby the term 'e' is used to normalise each greenhouse gas (GHG) relative to the impact of one unit of carbon dioxide (CO_2) (BSRIA, 2011). Thus, in relation to the framework equations (4-7), embodied energy (EE) would be replaced with embodied carbon (EC).

<Insert TABLE 4>

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 (m^2), volume (m^3), 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.

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.

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)

Results and Discussion

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.

<Insert TABLE 5>

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.

<Insert TABLE 6>

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 kgCO_2e respectively. Impacts per sub-contractor are displayed within Table 6 and 7.

<Insert TABLE 7>

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.

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 kgCO_2e respectively. Impacts per sub-contractor are displayed within Table 6 and 7.

<Insert TABLE 8>

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.

<Insert TABLE 9>

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).

<Insert TABLE 10>

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.

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.

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.

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.

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).

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.

Conclusions

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.

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