Measuring the embodied energy, waste, CO$_2$ emissions, time and cost for building design and construction

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Abstract
Successful mitigation of the climate change impacts can be achieved through development and implementation of robust strategies such as the use of low impact building design that seek to alleviate the impacts. The focus of the climate change or the environmental agenda in the construction industry (CI) has been put on the operational side of its product, i.e. building performance, with relatively little study on the impacts inherent from building design and construction. The paper argues that the costs of the energy, impacts of CO$_2$ emissions and waste that are implicit in building design and induced during the construction phase of a building are too enormous to ignore. Evidence from the literature reviewed suggests that little attention has been accorded to embodied energy, CO$_2$ and waste emissions with respect to the implications of design on construction. In order to effectively reduce the impacts during the construction phase, there is need for pragmatic mechanisms for assessing and measuring the impacts so that appropriate action can be taken to reduce them. The development of models for assessing embodied energy, CO$_2$ emissions and waste can help decision makers to choose appropriate technologies, building materials, systems and processes that can minimize impacts on the environment. Relevant computation models for measuring embodied energy, waste and CO$_2$ emissions are reviewed. The objectives are to identify the gaps in the current computation models, to reveal the relationships between the identified models and to propose a framework toward developing an integrated model for measuring embodied energy, waste, CO$_2$ emissions with an extension to include the time and cost functions of construction project management.

Keywords: CO$_2$ emissions, computation models, construction industry, embodied energy, waste

1 Introduction
The political pressure on governments in the world to address the adverse effects of climate change has been mounting. In response to the pressure, commitments have been undertaken by various governments through initiatives such as the Kyoto Protocol (DTI, 2004), the G5 and G8 summits (Florini and Sovacool, 2009). The UK government has been proactive toward reduction of CO$_2$ emissions. For instance, the nation is now legally bound to the Kyoto protocol to reduce its CO$_2$ emissions by at least 12.5% below the 1990 levels. Furthermore, the UK Government’s Climate Change Act 2008 sets a legally binding target of 80% reduction in national CO$_2$ emissions by 2050 compared to 1990 levels (DECC, 2009). To achieve these targets, mitigation strategies for CO$_2$ must be set up and implemented strictly across major sectors. In the UK, the CI is a major contributor to the emission of CO$_2$. Similarly, Sjostrom (2000) estimates that the construction and building sector could be responsible for about 40% of the overall environmental burden in the European Union and the United States.
CO₂ measurement is often linked directly to embodied energy as CO₂ is often the by-product of the production process. Embodied energy describes the amount of energy consumed by all of the processes associated with the production of a building, from the mining and processing of natural resources/materials to manufacturing, transport and then the delivery of the product (Milne and Reardon, 2008). For many years, embodied energy content of a building was assumed to be small compared to operational energy. The result is that most energy-related efforts on research have been directed toward reducing operational energy largely by improving energy efficiency of the building envelope. Milne and Reardon (2008) observed that according to a research by the Australian-based CSIRO (Commonwealth Scientific & Industrial Organisation), an average household contains about 1,000 GJ of energy embodied in the materials used in the construction of the house and this is equivalent to 15 years of normal operational energy. Weight and Rawlinson (2007) reported that the construction materials sector alone accounts for 5-6% of total UK emissions, with 70% of emissions being associated with the manufacturing and 15% being associated with the transportation of the materials. As compared to the total energy use in construction projects, embodied energy can account for as high as 40 – 60%. (Atkinson et al., 1996 cited in Menzies et al., 2007). Furthermore, research suggests that embodied energy in domestic buildings may be equivalent to 10 times annual operational energy use while for more complex commercial buildings, the ratio can be as high as 30:1 (Weight and Rawlinson 2007).

Like CO₂, it is unavoidable to totally eliminate waste in the construction process. Waste is any loss or additional expense caused by activities but do not add any value to the product. Many writers, including Koskela (1992), Alarcon (1993) Serpell et al. (1995) and Ishiwata (1997), have defined waste comprehensively by including aspects of time delays, quality costs, and lack of safety, rework, unnecessary transportation trips, long distances, and improper choice of management, methods or equipment. The significance of waste is explained by the fact that 40% of all landfill waste in the UK is building waste (Weight and Rawlinson, 2007). Using data from previous studies, Yahya and Boussabaine (2006) suggested an average of about 25% of construction materials are wasted during construction activities. They also argued that a reduction of on-site construction waste can reduce the recycling of demolition waste at the demolition stage of the construction life cycle. Bossink and Brouwers (1996) reported that the waste for each building material in the Netherlands lies between 1% and 10% of the amount purchased, with an overall mean of 9% of purchased materials becoming waste and according to Pinto and Agopyan (1994), the construction project-level waste rate in Brazil is between 20-30% of the total weight of material on site.

2 Challenges

Most techniques used for measurement of embodied energy, waste and CO₂ emissions are based on empirical studies using qualitative methods (Chen et al. 2005; Vonka 2005). They are useful to reveal the macroscopic impacts of the process but do not take into account the project specific issues such as the design, site layout construction methods, personnel and the technology used. Therefore, the use of these methods for project management is very limited. The use of computation models, as opposed to the qualitative methods, in determining embodied energy, construction waste and CO₂ emissions of the construction process can assist practitioners to produce low impact design in the design stage. Some shortcomings are identified by previous literature on the existing computation models. Firstly, while most computation models have been designed to quantify waste, CO₂ and embodied energy at the extraction, manufacturing, operational and demolition phases of the construction life cycle, very limited number of models have been developed to measure the impacts of on-site construction processes. Secondly, the most current computation models are independent to one another, i.e. models exist only for waste computation (e.g. Yahya and Boussabaine, 2006), or only embodied energy computation (e.g. Chen et al. 2005). Computer tools developed as end-user interfaces also exist in isolation. Ignoring the correlation between CO₂, embodied energy and waste can potentially lead to less-optimised design in terms of its impact to the three dimensions. Thirdly, the use of a number of single independent models to measure each impact can be time consuming and expensive. This shortcoming is further exacerbated by the fact that most models do not take time and cost into consideration. Therefore, the objectives of the paper are to identify the gaps in the current
computation models, to reveal the relationships between the identified models and to propose a framework towards developing an integrated model for measuring embodied energy, waste, CO$_2$ emissions, time and cost.

3 Review of computation models of embodied energy, CO$_2$, and waste

A recent review (Minx et al., 2008) identified the following three main methods for the calculation of the embodied greenhouse gas emissions of goods and services: process life cycle assessment (PLCA); input-output life cycle assessment (IOLCA); and hybrid life cycle assessment (HLCA). In PLCA, process data is used to compile the life cycle inventory (LCI) of a product. The data applied in PLCA may be collected directly or secondary data taken from LCI databases or other data sources assumed to be representative for a particular process. The development and use of life cycle inventories has become common practice, such as the widely used carbon and energy database developed by Hammond and Jones (2008) at Bath University. Input-output life cycle assessment (IOLCA) is a top-down method for analysing the environmental interventions of a product from cradle-to-gate based on environmental input-output analysis (Hendrickson et al. 2006; Seo and Hwang 2001; Treloar et al. 2001). Input-output analysis was developed by Leontief (1966) for analysing the industrial interdependencies in a national or regional economic system and later applied to environmental applications (Leontief and Ford 1970). The underlying input-output table is part of the national accounts and shows how much of an industry’s inputs are used to produce its own outputs. In HLCA, a combination of process, sectoral input-output, and environmental account data is used (Minx et al., 2008). Chen and Zhu (2008) present the following model which is representative of typically reported models for computing the environmental impacts from materials extraction and manufacturing.

$$I_{mi} = \sum_{j=1}^{n} (1 + \lambda_j) * m_j * \mu_{ji}$$

where $I_{mi}$ = an impact $i$ from materials extraction and manufacturing such as CO$_2$, SO$_2$, CO, NO$_x$ and PM$_{10}$; $j$ = the material concerned; $\lambda_j$ = the factor for waste of the material $j$ produced during the erection of the building; $m_j$ = the amount of material in Kg; $\mu_{ji}$ = the impact $i$ of emission factor from material $j$ during extraction and manufacturing.

Embodied energy can be computed from the CO$_2$ emissions by the use of a conversion coefficient. Simplified models exist for the calculation of the total construction waste (Yahya and Boussabaine 2006; Kumaran et al. 2001; Kourmpanis et al. 2008; Treloar et al. 2003). The model developed by Treloar et al. (2003) is particularly relevant since it is an attempt to relate waste to cost (see equation 2 below).

$$\text{TOTAL}_w S = \sum_{e=1}^{E} \sum_{m=1}^{M} [Q_{em} \times W_{em} \times P_m]$$

Where $\text{TOTAL}_w S$: the total cost of wasted materials; $Q_{em}$: the quantity of material $m$, in element $e$; $W_{em}$: the wastage rate (in %) for material $m$, used in element, $e$; and $P_m$: the unit cost of material, $m$.

4 Review of integrated time and cost models

Time-Cost computation models have been extensively reviewed (Wendling and Lorance 2000; Isidore and Back 2002). However, most of these models do not reveal a correlation between time and cost. Poh and Tah (2004) used a work breakdown structure (WBS) model to overcome the problem of the correlation which successfully links the two project dimensions, i.e. time and cost, together in their
The cost of a task in the WBS is evaluated based on the contribution made by the following resource components: materials, labour, plant and equipment, and subcontract. The development of the model involves three stages. First, it involves the estimation of duration required by the plant, labour (e.g. equation 3), sub-contractor components. The second stage involves the determination of the required task cost which depends on the labour (e.g. equation 4), plant and subcontractors involved in the task. The last stage is the estimation of the overall cost of the construction process (equation 5). Plant and labour are quantified based on the quantity of resources, their unit rates and duration on each task.

\[ T_{L,0} = \frac{QW}{(P_L \times Q_L)} \]  
\[ C_{L,0} = \sum (Q_{L,v} \times U_{R,L,v}) \times T_{L,0} \]  
\[ C_0 = C_{P,0} + C_{L,0} + C_{S,0} + C_{M,0} \]

where TL,0: the duration required to complete the task; QW: quantity of work of a task ;PL: labour productivity; QL: quantity of labour allocated

\[ C_{L,0} = \sum (Q_{L,v} \times U_{R,L,v}) \times T_{L,0} \]  
\[ C_0 = C_{P,0} + C_{L,0} + C_{S,0} + C_{M,0} \]

where CL,0: the labour cost of the task;QL,v: the quantity of labour type v; URL,v: the unit rate of labour type v

\[ C_0 = C_{P,0} + C_{L,0} + C_{S,0} + C_{M,0} \]

where C0: the total cost of task; CP,0: the plant cost of task; CL,0: the labour cost of task; CS,0: the total sub-contracting cost; CM,0: the material cost of the task. All the above cost variables are functions of time, unit rate of productivity and respective quantities.

5 Toward integrated embodied energy-CO2 emissions-waste-time-cost computation models

The ability to perform computations of low impact building performance indicators such as carbon, waste, time and cost simultaneously is a key element in realising an integrated approach. The literature reviews in sections 2 and 3 reveal that the models for computation of embodied energy, CO2 emissions, waste, time and cost have been developed and used in isolation. A review of equations (1) to (5) indicates they share similar parameters such as quantity of materials and waste although the definitions of similar parameters in different equations are not identical. Nonetheless, the quantity of materials is typically related to the size of the building components which makes it possible to develop an integrated model backboned with a series of equations that shares a set of common parameters. The development of the model will require the use of a significant amount of data and knowledge.

Current work of this research is focusing on extensive data collection from existing material and process inventories with carbon factors, construction methods and cost databases. This will be followed by knowledge acquisition from expert practitioners in the area of low carbon building design and construction using appropriate knowledge elicitation and representation techniques. One of the key elements to realising an integrated model is the establishment of inter-linked processes and the supporting integrated information infra-structure and databases. Process mapping techniques will be used to identify and map out the key process and decision points in the conceptual design process. This will draw on the RIBA plan of work, the OGC gateway process, and in-depth interviews with practitioners. The process models will identify the information requirements at each step in the conceptual design process.

The interoperability advancement in the emerging Building Information Modelling (BIM) tools provides an opportunity to implement the integrated model as quantity related data extractable directly from the tools can be used to facilitate the simultaneous computations required for assessment of cost, time, waste and CO2. Information exchange standards such as the ISO-STEP 10303, the Industry Foundation Classes (IFC), and the green building eXtensible Markup Language (gbXML) will be
used to extend existing ontologies and semantic standards to facilitate information interchange and interoperability between applications. A service-oriented architecture and open source Enterprise Service Bus (ESB) technology for message brokering, transformation and routing of data between individual applications as indicated in Figure 1 will be used. This will contain the interface modules managing the translation and conversion of data between different formats, and co-ordinating the flow of information between individual software components and applications. This will enable the individual software modules developed and the disparate BIM applications to work together as if they were designed to.

Figure 1, System Architecture

6 Conclusion

The integrated framework presented provides the opportunity to further investigate the links between embodied energy, CO₂ emission, time, cost and waste in a construction project. The paper summarizes and compares previous integrated computational models on project cost and time and identifies the potential to integrate them further with the CO₂ and waste dimensions which are the two key issues in sustainability debates. The complete integrated model as proposed in the paper can potentially improve the performance of buildings as designers or decision makers can assess the cost, time, waste and CO₂ of buildings at the design and construction stages through the use of the interoperable system described. Designers can benefit from the knowledge captured from the system and the databases to create low impact building design that is cost and time effective at the same time.

References


