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Mathematical modelling of embodied energy, greenhouse gases, waste, time–cost parameters of building projects: A review

F.H. Abanda*, J.H.M. Tah, F.K.T. Cheung

Oxford Institute for Sustainable Development, Department of Real Estate and Construction, Faculty of Technology, Design and Environment, Oxford Brookes University, Oxford OX3 0BP, UK

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ABSTRACT

The construction industry including its support industries is one of the highest consumers of natural resources. In the act of consumption of natural resources during construction processes, embodied energy and greenhouse gases are emitted which have adverse effects on the natural environment. Thus, recent studies have revealed a significant interest in the quantification of embodied energy and greenhouse gases in construction processes. Unfortunately, current interpretations and quantification procedures of embodied energy and greenhouse gases are quite unclear. More also, while greenhouse gas and embodied energy quantification models are so disaggregated, studies reveal their existence in isolation without any links to other important environmental/construction management variables such as waste, time and cost. The objectives of this study 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, greenhouse gases, construction waste, time and cost. The contributions of this study are three-fold. Firstly, the identification of the different models and variables, such that they can be used in computations, that can lead to consistent and comparable results. Secondly, investigate the relationships amongst embodied energy, greenhouse gases, construction waste, cost and time variables, that can facilitate the quantification process and hence potentially facilitate the engagement into low carbon building design by construction professionals. Lastly, lay the foundation for further research especially with regards to the integration of the different models and variables so that they can be measured simultaneously.

1. Introduction

It is now too well-documented that emissions from buildings contribute significantly to worsening the impacts of climate change on the environment. Due to the complex nature of environmental knowledge about greenhouse gas emissions, the quantification of these emissions is a huge challenge. Mathematical modelling has been widely utilised in science and engineering systems with high knowledge complexity. In such systems mathematical models are aimed at improving the understanding of the behaviour of systems, exploring new theoretical concepts, predicting system performance and in an increasingly number of cases, aiding in the solution of practical design problems. In the latter context, mathematical models offer the potential to reduce, or even to replace, the need for physical experimentation when exploring new material and/or process options [1]. Given the challenges and costs involved in conducting appropriate laboratory and pilot scale investigations, increased ability to assess new process options through mathematical modelling is highly encouraged.

With the sustainability agenda as top priority for most governments including the UK, many scholars have reported on different aspects of the environmental impacts resulting from environmental emissions in the life cycle of building projects. To provide a precise definition to the various environmental emissions, environmental indicators have been used to represent the different environmental emissions. Furthermore, to facilitate the quantification of the emissions, comprehensive life cycle assessment standards and specifications have been developed including: BS EN 15978 [2], ISO 14040 [3], Ecological Footprint standards [4] and BSI PAS 2050: 2011 specifications [5]. While all these standards are generic and can be applied to any product and process BS EN 15978 has been developed specifically for the assessment of the

* Corresponding author.
E-mail address: fabanda@brookes.ac.uk (F.H. Abanda).

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environmental performance of new buildings and refurbishment projects. Some life cycle assessments have been noted to lack consistency and their computational results revealed signification differences [6]. An important goal of life cycle assessment standards is to ensure consistency in computational methods, results and reporting [2]. Among the emissions that have impact on the environment, embodied energy and carbon dioxide (CO_2)- have recently gained ground in the construction industry [7–9]. Consequently, this study will focus on embodied energy and carbon. The energy embodied in new construction and renovation each year accounts for about 10% of UK energy consumption [10]. Yohanis and Norton [11] reported that embodied energy in a UK office building could be 67% of the operational energy over a 25-year period. Ürge-Vorsatz et al. [12] reported that buildings were responsible for 7.85 gigatonnes (Gt) of CO_2 emissions in 2002, equivalent to 33% of the global total energy-related emissions. In 2010, studies by Sturgis Associates reported the shares of embodied carbon (compared to operational carbon) in offices, warehouses, super markets and houses to be 45%, 60%, 20% and 30% respectively [13]). With improvement in technologies and increase use of legislation, the shares for all the afore-mentioned building types will increase to 95% in the next decade [13]. It is important to note that most literature tend to use the term greenhouse gases and environmental emissions rather than embodied CO_2. Consequently, given that CO_2 is a type of greenhouse gas, general models for the computation of greenhouse gases will also be considered appropriate for embodied CO_2 computation. Furthermore, embodied energy is increasingly becoming an important aspect used in the selection of construction materials, thus it is one of the key recommendations for the selection of building materials or construction products stipulated by the European Union (EU) Construction Products Regulation [14].

While reports on environmental impacts from construction projects are comprehensive and cover general methodologies and procedures for the computation of environmental emissions such as the input–output analysis and process models [15,16], very little attention has been paid on the exact mathematical models involved, less making a comparative analysis between the mathematical models underpinning these methodologies. This has often led to difficulties in establishing the "how", "why" and "what" questions easily captured in mathematical models [17]. Most comparative studies of the input–output and process analyses have been reported in the literature [15,16,18,19]. These studies tend to focus on issues such as ease of use, quality of results generated by each method, the outputs measured by the methods and the suitability or appropriateness of applications of the different methods. No study has actually examined the fundamental mathematical models often used in both input–output and process analyses. Hence, the following questions are often not easy to answer. How are the different variables in a given model related to each other? What is common between the variables of one model to the other? Can the subject of each model be easily changed? How can the models be integrated so as to easily quantify the different physical quantities (e.g. embodied energy) represented by the different variables independently and/or simultaneously?

Thus, this paper investigates how the questions stated in the preceding paragraph can be answered. This will be achieved through a review of the different mathematical models used in the computation of emissions from onsite construction activities using both the input–output and process analyses. Based on the fact that construction waste is a main output in construction projects, it is also important to review waste computation models in relation to construction emissions. Furthermore, the relationships of these parameters to conventional construction project performance indicators such as cost and time will be investigated to facilitate holistic considerations in assessments. The main benefit of linking the quantification models relating the parameters that underpin these models is to facilitate the real time independent as well as simultaneous evaluation of multiple performance indicators to support holistic decision-making in construction projects. On the one hand it is very unrealistic to include only one model published on different aspect of environmental emission quantification. On the other hand, it will be unrealistic to provide an exhaustive list of models on emission quantification. Nonetheless, a reasonable number of publications will be very useful for researchers in the field of low impact building design. The challenge is worth attempting and this paper is proposing a non-exhaustive review of emission quantification models in building construction processes including traditional cost-time performance models. In particular, 25 models constituting 54 equations were reviewed and presented in Appendix 1.

A background to the study is discussed with emphases on the different construction parameters to be investigated in the ensuing section. This is followed by a discussion on an overview of mathematical modelling applications and their significance. An examination of existing mathematical models, leading to the identification of the parameters underpinning the models presented in sections 4–6. This provided the basis for the proposal of a framework for the classification and analysis of the different models presented in section 7. The key findings of the analysis of the different models are discussed in section 8. In section 9, some guiding steps that can facilitate the development of an integrated model are discussed. The paper ends by a way of conclusion in section 10.

2. Background

In conventional project management project performance is assessed in three dimensions: time, cost and quality. The current threat posed by emissions from construction activities have shifted construction project management paradigm to include knowledge of environmental emissions emitted during the execution of construction processes. There is increasing pressure on the industry to design and construct buildings that induce minimal or no impact on the environment. In this regard, practitioners need information that can enable them to make informed decisions that address environmental impacts of buildings [20]. Targets related to environmental impacts are usually measured in embodied energy and embodied CO_2. Unlike project time and cost, embodied energy and CO_2 generated in projects are difficult to measure due to inadequate understanding of the emissions through a long-chained building process, the lack of accounting data and the lack of consensus on the scope and boundary for CO_2 measurement [21].

In the construction context, the development of accounting methods for embodied energy and CO_2 has been very limited and lacking coherence. Majority of models measure embodied energy and CO_2 of building materials [16,22] and the energy and CO_2 of buildings in operation [23]. Many of these models do not use the same measurement metrics and units. This is further exacerbated by the fact that results from any quantification of embodied energy and CO_2 depends greatly on the accounting technique pursued, thus rendering empirical validation of results difficult. In the literature, there appears to be a stronger incentive to monitor operational energy and CO_2 due to the view that the embodied contents of building materials is relatively small compared to those in operation. However, much recent literature [13,24] also indicates that with the progress being made in adopting measures that reduce energy consumption in buildings, embodied carbon will