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Towards a holistic modeling framework for embodied carbon and waste in the building lifecycle

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Abstract

As the building industry proceeds in the direction of low impact buildings, research attention is being drawn towards the reduction of carbon dioxide emission and waste. Starting from design and construction to operation and demolition, various building materials are used throughout the whole building lifecycle involving significant energy consumption and waste generation. Building Information Modelling (BIM) is emerging as a tool that can support holistic design-decision making for reducing embodied carbon and waste production in the building lifecycle. This study aims to establish a framework for assessing embodied carbon and waste underpinned by BIM technology. On the basis of current research review, the framework is considered to include functional modules for embodied carbon computation. There is a module for waste estimation, a knowledge-base of construction and demolition methods, a repository of building components information, and an inventory of construction materials' energy and carbon. Through both static 3D model visualisation and dynamic modelling supported by the framework, embodied carbon, waste and associated costs can be analysed in the boundary of cradle-to-gate, construction, operation, and demolition. The proposed holistic modelling framework provides a possibility to analyse embodied carbon and waste from different building lifecycle perspectives including associated costs. It brings together existing segmented embodied carbon and waste estimation into a unified model, so that interactions between various parameters through the different building lifecycle phases can be better understood. Thus, it can improve design-decision support for optimal low impact building development. The applicability of this framework is anticipated being developed and tested on industrial projects in the near future.

Keywords: BIM, embodied carbon, holistic design framework, low impact building, waste estimation

1 Introduction

Climate change has become a global focus in the world. Governments of many countries take great efforts to prevent climate hazard through laws, policies, and technological strategies. There is a lot of interest in energy efficiency for green building realisation in the built environment in order to avoid the side-effects on climate change. In the meantime, carbon dioxide emission and waste production are critical issues for the success of green building delivery. Inspired by the need for low impact buildings, investigations on reducing carbon dioxide emission and waste are conducted worldwide in order to achieve sustainable development in the built environment, and thus reduce climate change impacts.

Research about the reduction of carbon emission and waste is however fragmented in the built environment. Operational energy and embodied energy are two main sources of carbon dioxide emission. As a recognised factor, operational energy is extensively discussed (Sartori and Hestnes, 2007). Much effort has been put into reducing operational energy by improving the energy efficiency of the building envelope. Correspondingly, commercially available tools such as DesignBuilder, IES, etc. can be used for operating energy analysis. Embodied energy, however, has not been given much attention until recently as it was thought not to be significant compared to the energy used in operating the building over its life.

Research shows (Yohanis, 2002) that the embodied energy of a material can be the equivalent of many years of operational energy. In the boundary of 'cradle-to-gate', embodied energy includes all energy (in primary form) until the products leave the factory gate (Hammond and Jones, 2008). This embodied energy is mainly included in materials which are ready to be used before construction. Beyond the cradle-to-gate, energy consumption as well as waste production can also occur in the process of building construction, maintenance, and demolition (Reddy 2003; Reinders 2003). Therefore the reduction of embodied energy (carbon) and waste needs to be considered in the building lifecycle. Related software tools are still limiting in their ability to support such holistic design-decision making for low impact buildings.

Building information modelling (BIM) is emerging as a technology that can support design-decisions for reducing embodied carbon emissions and waste production in the building lifecycle. It is envisaged as having the potential to support holistic design decision making by handling the multitude of performance considerations involved in achieving low impact buildings. Being one of the enablers, the green building extensible markup language (gbXML) is devised to adopt green building principles for BIM tools. It has been supported in mainstream BIM products such as Autodesk Revit, Graphisoft ArchiCAD, Bentley Architecture, and etc. Furthermore, substantial 4D (3D plus time) /5D (4D plus cost) CAD investigations provide a feasible foundation to explore embodied energy and waste issues in a unified BIM framework. This holistic modelling framework, in conjunction with existing tools such as DesignBuilder, IES, etc., will benefit not only the reduction of both operational and embodied carbon emissions as well as waste in a specific building phase, but also the clarification of their interactions which can lead to optimal energy efficiency in the whole building lifecycle.

The aim of this study is to develop a unified framework for assessing embodied carbon and waste underpinned by BIM technology. In the following sections, embodied carbon and waste studies are reviewed first to highlight present research advancements and shortcomings. Subsequently, the holistic modelling concept is demonstrated to show the relationship between BIM application and embodied carbon and waste modelling in the building lifecycle. Based on these discussions, a modelling framework is proposed for its realisation followed by related future work and conclusions.

2 State-of-the-art

Building materials bring a great deal of embodied energy into the building production process. There have been quite a few investigations that concentrate on analysing embodied energy in specific building materials (Lenzen 2002; Reddy 2003; Reddy 2009). In order to estimate embodied energy/carbon in a wide range of building materials, research conducted by the University of Bath in the UK (Hammond and Jones, 2008) developed an inventory of carbon & energy (ICE) (The University of Bath, 2008). The inventory structured into 34 main material groups with over 1700 records on embodied energy (carbon), which are commonly used in the construction field. This ICE-database facilitates the 'cradle-to-gate' analysis of embodied energy/carbon in the built environment. It can serve the purposes of quantification and computation for embodied carbon estimations in the production of building.

There has been increasing research interest in the energy use in buildings from a lifecycle perspective. The lifecycle of a building is mostly differentiated into production, erection or construction, operation, maintenance and demolition (Thormark, 2001). Some studies target specific building types and regions to analyse embodied energy/carbon (Huberman 2008; Goggins 2009; Shukla 2009) in the building lifecycle. It is also indicated in these studies that embodied energy analysis in transportation and construction is dependent on specific situations such as on-site manufacturing methods and machinery utilisation. Related research (e.g. Pearce, 2007) demonstrated analytical approaches to transportation issues such as road selection, vehicle types etc. applying geographical 3D mapping based on Google Earth.

Waste estimation and avoidance is reported from all aspects in the building lifecycle using different methods and technologies. In the design phase, approaches such as the building waste assessment score (BWAS) (Ekanayake, 2004) and design information (Baldwin, 2008) etc are applied to estimate potential waste in targeted buildings. In the construction phase, information technologies such as GPS and GIS (Li, 2005) as well as bar-code (Chen, 2002) have been applied to the improvement of construction effectiveness. Additionally, on-site management via certain approaches, e.g. sorting (Huang 2002; Poon 2001), have demonstrated positive results in waste recycling in the construction and demolition phases.

Current research and practices imply that the estimation and reduction of embodied carbon and waste can be achieved in different building lifecycle phases. Reported methods and techniques however focus on one or several building materials, techniques and individual phases rather than in a holistic manner. Moreover, none of them utilised BIM for advanced quantification and simulation to both embodied carbon and waste. On-site management in both construction and demolition phases is critical for waste estimation and recycling. Leveraging advanced BIM technology, it is possible to develop integrated databases and knowledge-based systems for low impacted buildings to realise a holistic modelling framework.

3 BIM-based holistic modelling

BIM-driven environments are applicable to the design of low impact buildings because they are maturing in their interoperability with building performance assessment tools including integrated time and cost modelling. This allows us to take a holistic view in building lifecycle assessments in practice (Figure 1). BIM-based holistic modelling can be achieved via static visualisation and dynamic simulation for nD modelling assessment of embodied carbon and waste. Starting from static design to dynamic construction, operation, and final demolition, a BIM-based design decision tool is able to analyse embodied carbon and waste in the light of features of each building lifecycle phase. In the design phase, various building concepts and materials are explored and considered. Along with cost (budget) estimation within this phase, associated embodied energy/carbon contained in building materials can be accurately quantified in the boundary of cradle-to-gate. Potential waste generation can also be predicted according to elaborated design concepts. Supported by BIM, the design-decision in this phase can be considered in 6D (3D model plus embodied carbon, waste, and cost estimation) based on a visualised static 3D building model.

In the phases of construction, operation, and demolition, the design decision is a dynamic process where carbon dioxide emissions and waste production are closely related to construction activities and methods. Carbon emission and waste production is likely to occur in the boundaries of manufacturing for building construction, maintaining for building operating and routine repairing, as well as recycling and disposing of building components and materials. It is noted that operating and embodied carbon emission can be occurred simultaneously in the maintaining boundary. These dynamic features necessitate a simulation approach to analyzing embodied carbon and waste production. Moreover, this dynamic simulation can also examine static design concepts in terms of embodied carbon and waste reduction. Available 4D/5D CAD techniques provide a viable approach to this dynamic solution. By utilizing BIM for integrated real time analysis, it is thus possible to evaluate time, cost, embodied carbon, and waste (7D) in the entire building lifecycle.

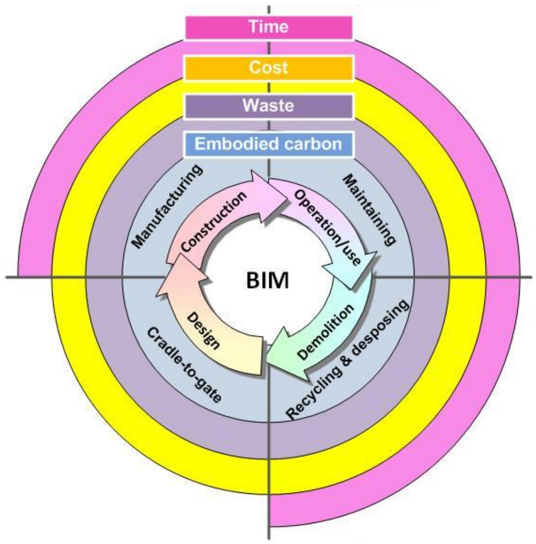

Figure 1. Holistic nD modelling in the building lifecycle

4 Proposed modelling framework

A holistic nD modeling framework for embodied carbon and waste reduction is proposed to take the advantage of service-oriented architecture (SoA) to satisfy the 7D modeling needs. Within this software architecture, service requester, service provider and middleware contribute to related modules and functionalities (Figure 2). Its associated software development needs to establish robust methods, protocols, and rules for measuring carbon emissions/avoidance from construction materials and waste, components, and activities. Its open structure also considers interoperability between existing software tools and state-of-the-art BIM-driven software environments.

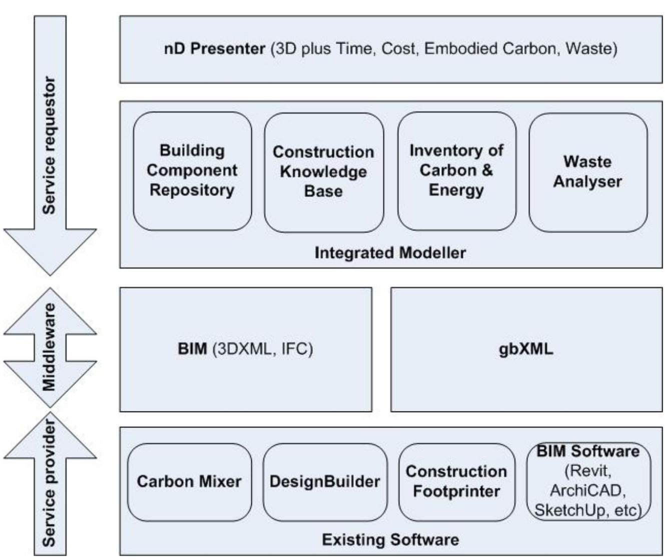

Figure 2. Software architecture of holistic nD modeling

In the framework, existing software like Google SketchUp as the service provider can be used for design concept exploration in the design phase. Some third parties have already developed plug-ins in SketchUp, e.g. LiveEnergy Modeller, to export/import gbXML for green building designs based on

3D model. This practice makes it possible to check embodied carbon in the early design phase. Other commercially available tools like DesignBuilder, IES, etc., targeting construction and operation phases for analysing energy efficiency, can also create this data interface to achieve interoperability with BIM-based toolkits.

The middleware handles the interpretation of gbXML and BIM file formats like 3DXML and IFC (Industry Foundation Class) and message routing between the service provider and the service requester. The gbXML contains necessary information for green building designs for energy efficiency whilst the 3DXML or IFC conveys BIM to express building objects' features and attributes. Their combination ensures that conceptual green building designs from SketchUp are exported into other BIM software such as Revit, AchiCAD, or Digital Project for detailed designs. Refined designs in these BIM environments can also be outputted in the format of 3DXML or IFC and gbXML to the service requester, which can perform design-decision making subsequently.

The service requester is a nD presenter playing a pivotal role in the framework. It is compatible with the discussed middleware to import gbXML and BIM files for energy efficiency and waste avoidance analysis. Its supporting infrastructure, named integrated modeller, encompasses several key modules of building component repository, construction knowledge base, inventory of embodied energy/carbon, and waste analyser. The building component repository stores all green building information obtained from middleware. The construction knowledge base provides construction/demolition methods, plans, and legacy data for construction/demolition choice. It can help create possible scenarios or strategies of construction, operation and demolition for dynamic analytical simulation. The embodied energy/carbon inventory contains cradle-to-gate information of construction materials for modelling reference. The waste analyser module represents approaches and mathematical models for waste avoidance analysis. These modules constitute the integrated modeller as 7D presenter's foundation for reducing embodied carbon and waste through static visualisation and dynamic simulation in different building lifecycle phases.

5 Future work

The development of the integrated modeler will be imperative for the success of holistic modeling. Related work is identified to be the connection of the building component repository with the embodied energy/carbon inventory. By incorporating BIM and gbXML with embodied energy/carbon references, the quantification of embodied carbon is achievable in green building designs on the basis of advanced BIM technology. Moreover, the development of construction knowledge base needs considerations of specific construction methods, protocols, and techniques. It is the foundation of dynamic construction/demolition simulation for reducing embodied carbon and waste in the process. Additionally, refinement of various mathematical models and techniques for waste estimation and avoidance will be undertaken in order to suit application needs from different building phases in the lifecycle.

6 Conclusion

The proposed holistic modeling framework provides a possibility to analyze embodied carbon and waste from different building lifecycle perspectives including associated costs. It brings together existing fragmented embodied carbon and waste estimation into a unified model, so that interactions between various parameters through the different building lifecycle phases can be better understood. Thus, it can improve design-decision support for optimal low impact building development, and deliver a new design-decision toolkit. The tool's applicability is anticipated being tested on industrial projects in the near future.

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