DEVELOPMENT OF A LOCAL EMBODIED CARBON DATABASE FOR CONSTRUCTION MATERIALS

Jack C.P. Cheng[1], Irene M.C. Lo, Vincent J.L. Gan, Ran Jing, Jing L. Zhang

Department of Civil and Environmental Engineering,
The Hong Kong University of Science and Technology,
Clear Water Bay, Kowloon, Hong Kong

1 Corresponding Author E-mail: cejcheng@ust.hk, Tel: (852) 2358-8186, Fax: (852) 2358-1534

DEVELOPMENT OF A LOCAL EMBODIED CARBON DATABASE FOR CONSTRUCTION MATERIALS

ABSTRACT

According to WWF, the construction sector was the second largest contributor to Hong Kong carbon footprint and emitted nearly 4 million tons of carbon dioxide in 2007. In addition to the operational carbon generated during building operation and maintenance, the embodied carbon of construction materials also contributes a significant part of the life cycle carbon emission in the built environment. Studies have shown that the embodied carbon of buildings is close to the operational carbon over 20 years, and contributes more than 30% of the life cycle carbon emission of buildings. In Hong Kong's construction sector, 85% of its carbon footprint was embodied in imported goods and services. Therefore, it is crucial to study the embodied carbon of construction materials and select the low carbon materials in order to achieve a low carbon built environment. This project aims to develop a local embodied carbon database, namely ECO-CM (Embodied Carbon Of Construction Material), for the commonly used construction materials in Hong Kong. A "Cradle-to-Site" life cycle boundary was used in the ECO-CM database, which includes raw materials extraction and transportation, material manufacturing, and product transportation to the use site. As the fuel mix and material manufacturing and delivery in different areas may vary substantially, embodied carbon values are region-specific. Therefore, first hand data were collected from the material vendors through questionnaires for calculation. The methodology framework used in the development of the ECO-CM database is presented and illustrated in this paper. The completed ECO-CM database will provide a basis for selection of green materials, development of carbon labels, and estimation of building facility carbon footprint, thereby helping to construct a low carbon Hong Kong.

Keywords: *Cradle-to-Site; Embodied Carbon; Green Construction Materials; Life Cycle Assessment.*

1. INTRODUCTION

The global warming issue has attracted a great concern around the world in recent years. Greenhouse gas (GHG), a gas which absorbs and emits radiation within the thermal infrared range, is the major cause of global warming. United Nations Framework Convention on Climate Change has agreed that the future global warming should be limited to below 2.0 °C (UNFCCC, 2010). According to WWF, the building construction sector is the second largest contributor to Hong Kong carbon footprint (Cornish *et al*., 2011). Moreover, it was generally agreed that since the sources of Hong Kong's carbon emissions are concentrated in the power sector and building sector, the greatest opportunity for Hong Kong to reduce its emissions lies in these two sectors (Cornish *et al*., 2011). Embodied energy and carbon have attracted much attention recently. It has been shown that embodied energy and carbon can greatly influence the life cycle energy consumption and carbon emission of contemporary buildings. Therefore, estimating the embodied carbon of commonly used construction materials can help to provide a basis for prediction and reduction of GHG emissions in the construction sector.

Application of green construction materials plays a significant role in the carbon reduction of construction sector. There are several life cycle embodied carbon databases for the selection of green construction materials, such as Ecoinvent developed by the Swiss Centre for Life Cycle Inventories, the Inventory of Carbon and Energy (ICE) by the Bath University, and the Chinese Life Cycle Database (CLCD) by the Sichuan University. In Hong Kong, a local embodied carbon database namely Embodied Carbon of Construction Materials (ECO-CM) is under development by the Hong Kong University of Science and Technology (HKUST).

The ECO-CM has several differences compared with other databases. First of all, the system boundary of this study is “Cradle-to-Site”, which covers partial product life cycle from raw material extraction to final product transportation. The CO_2, CH_4 and N_2O emitted in the “Cradle-to-Site” life cycle boundary are considered in the calculation of GHG emissions. Moreover, this project targets to conduct Hong Kong-specific estimation of CO_2 emission using the first-hand data from material manufacturers and vendors. The first hand data were collected via company-level questionnaire surveys and interviews with stakeholders.

Table 1: Life Cycle Inventories of Construction Material in Different Countries

Region	Construction Life Cycle Inventory (LCI)	Institution	System Boundary
Switzerland	Ecoinvent	Swiss Centre for Life Cycle Inventories	Gate-to-Gate
Europe	ELCD (European reference Life Cycle Database)	European Union	Cradle-to-Gate
United Kingdom	ICE (Inventory of Carbon and Energy)	University of Bath, UK	Cradle-to-Gate
China	CLCD (Chinese reference Life Cycle Database)	Sichuan University, China	Cradle-to-Gate
Hong Kong	Embodied Carbon Of Construction Materials (ECO-CM)	HKUST	Cradle-to-Site

The embodied carbon values are region-specific. However, estimation of embodied carbon in the construction materials used in Hong Kong still relies heavily on overseas data, which may not be applicable to the construction industry in Hong Kong. A local carbon inventory database for construction materials will be a good reference for property developers, architects, engineers, contractors, procurement officers, and material suppliers to optimize their design, construction, and logistic approaches for GHG emission reduction.

The content of this paper is organized as follow: Section 2 describes the methodology framework adopted in this project with consideration of local factors; Section 3 provides an illustrative example about the calculation of embodied carbon; Section 4 concludes the paper and discusses the potential application of the ECO-CM database.

2. METHODOLOGY

The LCA methodology framework in this project is developed with reference to the stages and requirements described by ISO 14040:2006 (ISO, 2006), ISO 14044:2006 (ISO, 2006) and Publicly Available Specification (PAS) 2050:2008 (defra, 2008). As shown in Figure 1, the methodology framework consists of four main stages: (1) background study, (2) system boundary setting, (3) life cycle inventory analysis (LCI), and (4) result analysis and reporting.

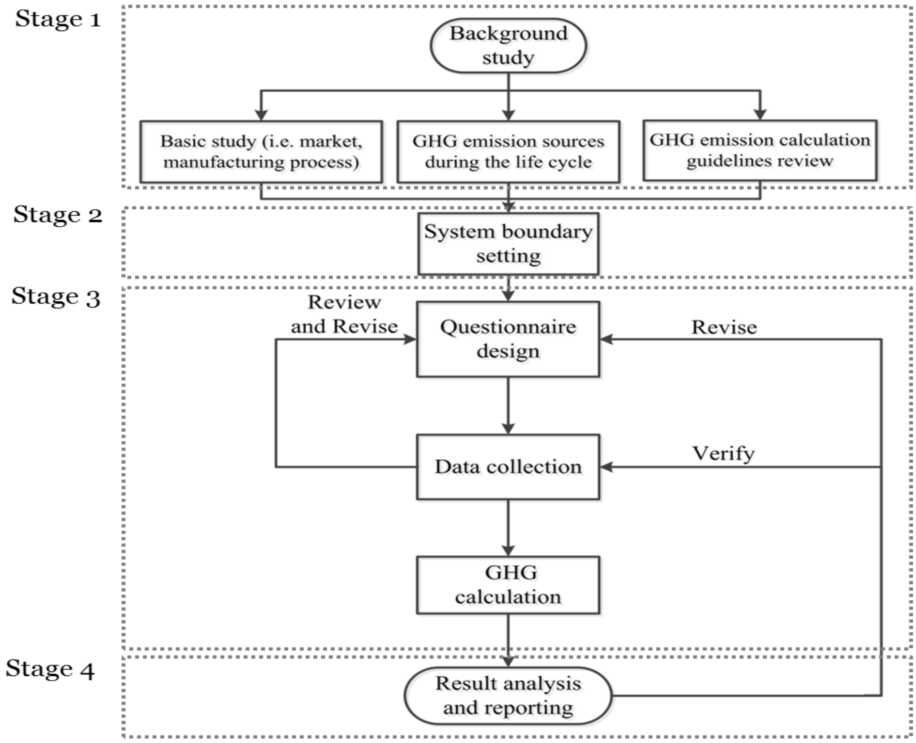

Figure 1: Methodology Framework for Life Cycle Carbon Measurement

2.1. BACKGROUND STUDY

The purpose of background study is to ascertain the main features of a material including the characteristics, classification, manufacturing process and product market share. Literature review for material classification refers to international/regional specifications (e.g. ISO, The American Society for Testing and Materials (ASTM)) and existing databases such as ICE and Ecoinvent. Material classification differentiates the materials for construction purpose and non-construction purposes. Following the material classification, the market share information for the construction materials will be collected and the manufacturing process will be investigated. Finally, with respect to the material manufacturing process, the GHG emission sources are identified stage by stage from raw material extraction to final product transport.

2.2. DETERMINATION OF SYSTEM BOUNDARY

System boundary separates the internal components of a construction material system from externalities. The purpose of system boundary setting is to determine the scope of study. As shown in Figure 2, the material system is divided into a series of unit stages including raw material extraction, product manufacture, final product transport, material use, disposal and recycling. Raw material extraction refers to "Cradle", which means the start of a material life cycle. Correspondingly, material disposal refers to "Grave", which means the end of a material life cycle. System boundary setting should cover a set of stages over the full material life cycle such as "Cradle-to-Gate" and "Gate-to-Gate". The stages within the system boundary are the focus of the life cycle analysis. In ECO-CM, calculation of material embodied carbon is examined with respect to the "Cradle-to-Site" life cycle, which covers raw material extraction to packing and shipping the final products.

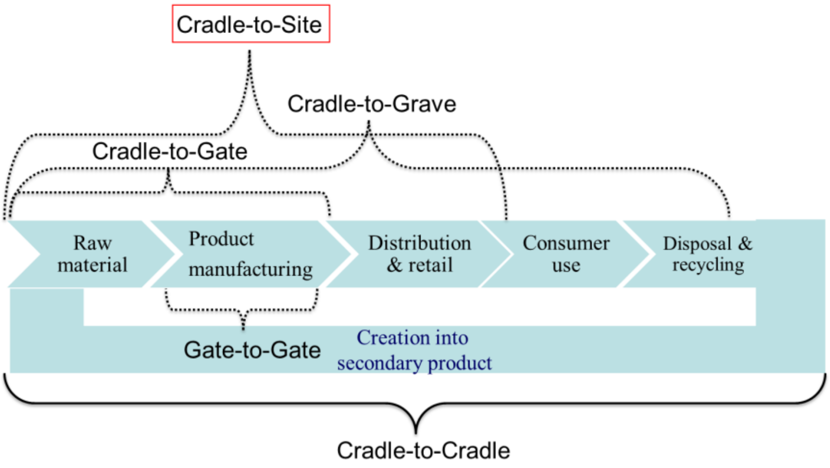

Figure 2. Different Life Cycle Boundary of a Product System

2.3. LIFE CYCLE INVENTORY ANALYSIS

LCI involves creating and quantifying the relevant "inputs" and "outputs" of a material system during the "Cradle-to-Site" life cycle. The inputs refer to fossil fuel, electricity, raw materials while the outputs refer to emissions to air, discharge to water and soil, etc. In this project, the "inputs" and "outputs" are collected from material manufacturers and vendors through questionnaire survey. Some common questions are raw material usage, transportation means, location of the suppliers, consumption of fuel and electricity, etc.

Following the data collection, first-hand data from material manufacturers and vendors are used to calculate the embodied carbon in the "Cradle-to-Site" life cycle boundary. The calculation of embodied carbon is consistent with the standard GHG auditing guidelines, such as International Panel on Climate Change Guidelines for National Greenhouse Gas Inventories (IPCC, 2006) and the Greenhouse Gas Protocol (WRI and WBCSB, 2011). Some calculation considerations are the embodied carbon of raw materials, the emissions from energy consumption, as well as the emissions from final product transport. In some special cases, non-energy emission should be considered, such as the CO_2 emitted during raw materials calcination in the process of manufacturing cement.

2.4. RESULT ANALYSIS AND REPORTING

The final stage of the methodology framework is to analyse and report the material embodied carbon from LCI. For example, result analysis can identify and compare the proportion of gaseous emissions in different stages during the material life cycle. In this way, people can identify the stages that emit the largest amount of GHG and the optimal solutions of minimising the quantity of gaseous emissions. On the basis of the analysis results, the reporting stage should provide some key findings and recommendations for material development and improvement.

3. ILLUSTRATIVE EXAMPLE OF PORTLAND CEMENT

In this section, an illustrative example is provided to demonstrate the calculation of embodied carbon of cement. First of all, the background study investigates the current cement market in Hong Kong. The system boundary of Portland cement includes raw material extraction and quarrying, raw material transport, cement manufacturing, and final product transport. After extraction and quarrying, the raw materials, which are clay, limestone, iron ore and sand, are transported to cement factory. The raw materials are grinded to fine powder and are mixed preparing for calcination. Under a temperature of 1400 ℃ -1500 ℃, the clinker is produced and CO_2 is emitted. The last phase is the transport of the cement product to the construction sites. The accuracy of the GHG emission calculation depends on the availability and quality of the data collected from the manufacturers. Therefore, a bilingual questionnaire (English and Traditional Chinese) for cement manufacturers was designed. The questionnaire contains 11 parts which are consistent with the GHG emission sources during the material life cycle. The GHG emissions calculation method involved in this study follows the IPCC Guidelines for National Greenhouse Gas Inventories. After GHG emission calculation, revision of the questionnaire and verification of the data were needed for keeping results accuracy and data consistency.

Table 2: Results of CO_2-e for Each Part of Cement Life Cycle

(1) Upstream material	**kg CO_2-e/kg clinker**	**Percentage**	**kg CO_2-e/kg cement**	**Percentage**
Limestone	3.718×10^{-3}	-	3.222×10^{-3}	-
Sand	2.358×10^{-4}	-	2.043×10^{-4}	-
Clay	2.309×10^{-4}	-	2.002×10^{-4}	-
Iron ore	8.785×10^{-5}	-	7.614×10^{-5}	-
Coal	1.868×10^{-2}	-	1.619×10^{-2}	-
Total CO_2-e (1)	**2.295×10^{-2}**	**2.17%**	**1.989×10^{-2}**	**1.97%**
(2) Concrete batching	**kg CO_2-e/kg clinker**	**Percentage**	**kg CO_2-e/kg cement**	**Percentage**
Calcination	0.551	52.08%	0.478	47.33%
Coal combustion	0.348	32.89%	0.302	29.90%
Electricity consumption	0.051	4.82%	0.08	7.92%
Imported clinker	NA	-	0.058	5.74%
Total CO_2-e (2)	**0.95**	**89.79%**	**0.918**	**90.89%**
(3) Transport	**kg CO_2-e/kg clinker**	**Percentage**	**kg CO_2-e/kg cement**	**Percentage**
Limestone	5.225×10^{-2}	-	4.528×10^{-2}	-
Sand	3.544×10^{-4}	-	3.071×10^{-4}	-
Clay	2.835×10^{-4}	-	2.457×10^{-4}	-
Iron ore	2.130×10^{-3}	-	1.846×10^{-3}	-
Imported clinker	4.474×10^{-3}	-	3.877×10^{-3}	-
Coal	2.163×10^{-2}	-	1.875×10^{-2}	-
Cement	3.770×10^{-3}	-	3.267×10^{-3}	-
Total CO_2-e (3)	**8.489×10^{-2}**	**8.02%**	**7.357×10^{-2}**	**7.28%**
Total CO_2-e	**1.058**	**100%**	**1.01**	**100%**

The calculation results of the illustrative example are summarized in Table 2. As shown in Table 2, the cement manufacture process emits 0.918 kg CO_2-e/ kg cement and accounts for the highest contribution (90.89%) of the total GHG emission during the cement life cycle. The following contributor is raw material and the final product transport, which is 7.28% of the total GHG emission. On the other hand, raw material extraction contributes the least CO_2 emission due to much less energy consumption compared with the manufacturing process. Calcination of carbonates is the major source of CO_2 emission, which accounts for 47.33%. Coal combustion, accounting for 29.90% of total emissions, is another important source. Moreover, CO_2 emission caused by electricity consumption and import clinker account for 7.92% and 5.74% of CO_2 emission of manufacturing process, respectively. The total GHG emission of the illustrative example is 1.01 kg CO_2-e/ kg cement. The results from different sources will be aggregated for each construction material in the ECO-CM database.

The results of calculation of each construction material could be directly used to support the environmental performance assessment of a building according to recent standardization work. For other construction materials involved in this study, such as concrete, glass, steel, aluminium, and ceramics, the embodied carbon will be calculated using similar methodology as described in cement study. Finally, the result of GHG emissions calculation over “Cradle-to-Site”, “Cradle-to-Gate” and “Gate-to-Gate” life cycles will be summarized for developing the ECO-CM database.

4. DISCUSSION

Unlike ICE and Ecoinvent which use the “Cradle-to-Gate” material life cycle, ECO-CM considers the product life cycle from raw material extraction (Cradle) to transportation of the construction material (Site). Moreover, in ECO-CM, first hand data from material manufacturers and vendors are collected and used to calculate the material embodied carbon. Therefore, the life cycle inventory data from ECO-CM provide a more accurate and local specific estimate of GHG emission from construction materials. ECO-CM provides several benefits to the local construction industry:

(1) Green construction materials selection: In Hong Kong, there is a trend to consider the utilization of green construction materials in the green building evaluation system (i.e. BEAM Plus). The evaluation system encourages contractors to utilize green construction materials during the building construction stage. Under such circumstances, the ECO-CM database provides a benchmark for evaluation and selection of the green construction materials.

(2) Prediction of GHG emission: The ECO-CM provides a guideline for prediction of GHG emission in material production as well as the GHG emission embodied in buildings and infrastructures. For example, cement manufacturers can use the gate-to-gate embodied carbon to estimate the GHG emission in cement production. For a building project, the “Cradle-to-Site” embodied carbon of each material can be applied to calculate the embodied carbon of a building.

(3) Development of green construction materials: The ECO-CM provides the amount of GHG emitted in different stages during the material life cycle. The information can help identify the stage that incurs serious contaminations and the optimal solution in reducing the GHG emissions. In this way, the environmental performance of a material can be improved because the gaseous emissions during the material life cycle are reduced.

REFERENCES

Cornish, A., Larson, J. et al. January 2011. Hong Kong Ecological Footprint Report 2010:Report to the World Wildlife Fund (WWF). Hong Kong.

defra. 2008. *PAS 2050:2008 - Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Service*. UK.

International Organization for Standardization. 2006. *ISO 14040:2006 Environmental Management Life Cycle Assessment – Principles and Framework*. Switzerland.

International Organization for Standardization. 2006. *ISO 14044:2006 Environmental Management -Life Cycle Assessment - Requirements and Guidelines*. Switzerland.

International Panel on Climate Change. 2006. *Guidelines for National Greenhouse Gas Inventories*. Japan.

United Nations Framework Convention on Climate Change (UNFCCC). November, 2010. *Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010*. Cancun Climate Change Conference. Cancun.

WRI and WBCSB. 2011. *Greenhouse Gas Protocol - Product Life Cycle Accounting and Reporting Standard*.US.