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An attributional and consequential life cycle assessment of substituting concrete with bricks

Harn Wei Kua*, Susmita Kamath

Department of Building, School of Design and Environment, National University of Singapore, 4 Architecture Drive, Singapore S117566, Singapore

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ABSTRACT

Singapore introduced the Concrete Utilization Index to promote the substitution of concrete products with alternate building materials. This study examined the environmental impacts of replacing concrete with bricks. Using an attributional life cycle approach, it was found that replacing concrete with bricks may actually increase the net environmental impacts. In the first ever consequential life cycle assessment done for bricks in the literature, we found that replacing concrete with bricks may result in small reduction in global warming potential, provided there is no change to the amounts of bricks and concrete constituents being imported into Singapore. Considering there are changes to the import quantities, we derived a mathematical relation that enables us to know how much the import of concrete constituents must decrease in order to nullify the increased global warming potential resulted from the increase in import of bricks. In all these assessments, we found that the environmental impacts (including global warming potential) of the manufacturing stage of bricks need to be reduced. To achieve this, we reviewed a few new brick-making approaches that can produce more sustainable bricks; we also proposed a way of creating a “green demand” for these bricks and utilizing policies such as Singapore's Business Angel Scheme to finance the upgrading of brick-making technologies through international partnership.

1. Introduction

Singapore's Green Mark Scheme (GMS) – the green building standard created and implemented by the Building and Construction Authority (BCA) – plays an important role in promoting sustainable design and construction in the building industry. In the latest version of the GMS, a Concrete Utilization Index (CUI) is prescribed; it is defined as the total volume of concrete used in a building per unit gross floor area. If a design has a CUI of less than 0.3, it will be awarded with the maximum of 5 points under the GMS for this criterion. The CUI was proposed to encourage the industry to reduce the reliance on concrete, which will in turn reduce the dependence on its constituents, such as sand and granite. It also aims to promote the replacement of concrete with other structural materials. For structural purposes, concrete can be replaced with wood, steel or bricks. Traditionally, wood is not widely used for construction in Singapore. While steel can be used to replace concrete columns, beams and, less commonly, slabs, it is not used to replace concrete in shear walls. Replacing concrete entirely with steel will decrease the walls' thermal resistance and increase the cost of construction. By contrast, bricks have similar thermal resistance as concrete blocks and have been widely used in Singapore in shear walls and internal light structural walls. In other words, there are more possibilities to replace concrete with bricks in Singapore.

Since its inception, there has not been a systematic and rigorous way of assessing the effectiveness of CUI in promoting sustainable construction, particularly as a result of substituting away concrete. The aim of this study is to apply the concept of life cycle assessment (LCA) to evaluate the resultant environmental impacts of replacing concrete with masonry (bricks, specifically), which is becoming a common strategy to achieve a lower CUI.

Concrete is arguably the most important and versatile material in construction today. It is composed primarily of cement, aggregates and water. Each year, more than 10 billion tonnes of concrete are produced globally for use in construction projects (Thi Do, 2011). It is estimated that the amount of concrete used in the construction industry is almost twice that of all other building materials put together (UNEP, 2003). Owing to its strength, durability and ease of casting, concrete is used in a variety of

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* Corresponding author.
E-mail addresses: bdgkuahw@nus.edu.sg (H.W. Kua), susmita.kamath@gmail.com (S. Kamath).

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applications in the construction industry. Cement, the main constituent of concrete, is a major source of greenhouse gases (GHGs). It is estimated that the cement industry contributes about 5–7% of the global anthropogenic CO_2 emissions (UNEP, 2003). The production of concrete also causes extensive quarrying for sand, gravel and stones for use as aggregates in the concrete mixture. The construction industry is by far the only consumer of bricks (Rose et al., 1978). Bricks are one of the oldest and most popular building materials, owing to their low price, durability and ease of handling. Bricks are known to retain their colour much longer than concrete blocks. Furthermore, concrete absorbs water at a rate higher than bricks, thus causing larger changes in the dimensions of concrete blocks when they are being used. The thermal resistance of bricks and concrete blocks are similar and so replacement with bricks is unlikely to change the energy consumption of the building during the use phase. However, it is well known that brick making is an energy intensive process. In 2008, the Asian brick making industry consumed about 110 million tons of coal and the diesel used for transportation produced approximately 180 million tons of carbon dioxide (CO_2) (Heierli and Maithel, 2008).

LCA is a popular and rigorous method for assessing the total environmental impact of building materials. While applying LCA to assess the environmental impacts of bricks, we need to take into account the net environmental impacts caused by the replacement of concrete by bricks. This study analysed the net impacts of such a replacement, using both an attributional LCA (ALCA) and consequential LCA (CLCA).

ALCA calculates the environmental burdens resulting from a given product, whereas CLCA considers higher order effects, including the net environmental impacts due to market response to material substitution (Earles and Halog, 2011). In other words, CLCA extends the system boundary beyond what the conventional ALCA considers. Most of the available literature on LCA for bricks is ALCA in nature. For example, a detailed ALCA was carried out for the manufacturing of clay bricks, with respect to energy consumption and CO_2 emissions, by Koroneos and Dompros (2007). It was a cradle-to-gate study that studied the life cycle stages of raw material extraction, brick manufacturing, packaging and transportation. Owing to the difference in processes employed for manufacturing and the difference in composition of clay from region to region, a large variation is obtained in embodied energy of bricks. It varies from 2200 MJ/tonne (Ashby, 2009) to 5909 MJ/tonne (Utama and Gheewala, 2008). In comparing brick and concrete, Venta (1998) conducted a cradle-to-gate study in Canada to analyse the inputs and outputs from brick production; it was found that the embodied energy and the emissions due to the manufacturing and transportation were substantially higher for clay bricks than concrete (for a functional unit of one cubic metre of bricks). Utama et al. (2012) studied the embodied energy of houses in Indonesia that might use either clay bricks or concrete blocks for their envelopes. The embodied energy of clay bricks was found to be half of that of concrete blocks, due to the manufacturing process employed and the tropical weather in the country. The results indicated that clay bricks perform better in global warming potential (GWP) and human toxicity potential (HTP), whereas concrete blocks fare better in acidification potential (AP), eutrophication potential (EP) and photochemical oxidation potential (PCOP). The AP impacts in clay bricks were mainly due to presence of hydrogen fluoride and chloride in the clay. The usage of higher amount of mortar for clay bricks and its replacement also contributed to the AP.

In comparison, CLCA for buildings materials has been rare. In the first CLCA study in the Singapore context, the effects of substitution of cement with copper slag were analysed (Kua, 2012). The results of ALCA suggested that the substitution is desirable; however, the CLCA indicated a reduction in the benefits of such a substitution. Presently, there has not been any CLCA on the replacement of concrete products with bricks anywhere in the world. The need to assess possible consequences of the CUI in Singapore provides us with the motivation to conduct such a CLCA, in order to fill this important knowledge gap in the literature.

2. Materials and methods

2.1. System boundary of brick

The assessments carried out in this study were for a functional unit of 1 kg of clay bricks. Data for this paper was acquired mainly through literature review, questionnaires, telephone interviews and emails correspondence with relevant stakeholders in the industry. When necessary, the information gathered was further modified to suit the Singapore context, for example by applying local electricity fuel mix and the estimation of transport emissions specific to the specific cases being studied. The results of both materials were then analysed from an ALCA and CLCA perspective.

The characterization factors for various inputs were taken from the ECOINVENT database (ECOINVENT, 2010). For the ALCA, the focus was put on five impact categories, namely GWP, AP, EP, HTP and Cumulative Energy Demand (CED).

The inputs considered for all life cycle stages are primarily electricity, diesel and water. In the literature, it was noted that the liquid and solid wastes generated during brick life cycle are negligible (Koroneos and Dompros, 2007; Venta, 1998). Hence, our study focused only on gaseous emissions.

The major suppliers of bricks for Singapore are located in Malaysia (specifically in the state of Johor). Bricks from Malaysia are usually manufactured in large automated plants. Hence, we modelled the life cycle of bricks according to the processes in such a plant. In calculating the impacts due to transportation, we first calculate the “tonne-kilometer” (measured in tkm) of the materials involved. Tonne-kilometre is the unit of measurement for the transportation of 1 tonne of a material by a given transport mode over a distance of 1 km. The CO_2 emission due to transportation is then computed by multiplying the value of tonne-kilometer by the emission factor (in kg_{CO_2}/tkm) and the total mass of material transported (Cefic-ECTA, 2011).

Fig. 1 illustrates the processes that are within and beyond the scope of study. Each of these life cycle stages are described as follow:

2.1.1. Raw material extraction

The raw material used is clay from two quarries near the manufacturing unit (Worrell et al., 1994). The equipment used for this operation is digging and excavation equipment that runs on diesel. We considered the manufacturing unit (in Johor) to be located within a 5–10 km radius around the quarries (Utama et al., 2012). For 1 kg of clay bricks, 1.11 kg of clay is required. The average distance between the quarry and the manufacturing plant is 15 km. Hence, the tonne-kilometer is

$$15 \times \frac{1.11}{1000} = 0.017 \text{ tkm} \qquad (1)$$

By multiplying this value to the emission factor (in kg_{CO_2}/tkm) of the 40-tonne truck, the CO_2 emission can be found (Cefic-ECTA, 2011). The other outputs and environmental impacts due to transportation were found by estimating the total amount of fuel used for the transportation and multiplying it by the factors

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