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The embodied air pollutant emissions and water footprints of buildings in China: a quantification using disaggregated input–output life cycle inventory model

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ABSTRACT

Building has complex supply chains involving different sectors in a national economy. Although input–output life cycle inventory (I–O LCI) model enables economy-wide footprint calculations, the model is vulnerable to sector aggregation and is thus unsuitable for individual product analysis. This study employed a disaggregated I–O LCI model that divides the construction sector in China into thirteen building sub-sectors to fill the national inventory data gap in building embodied emissions and water footprints. Results show that public buildings have larger footprints than residential buildings because of their heavy structural designs that significantly depend on steel and cement consumption. Compared to rural residential buildings, the footprints of urban residential buildings are 55–130% greater. Materials efficiency enhancement is a promising pathway to building embodied footprints mitigation and the use of an applied technology—the near net shape casting—would offer China an annual greenhouse gas (GHG) mitigation potential of 5.2 million metric tons of CO_2e. This study presents complete and specific calculations for building embodied emissions and water footprints in China. Study results fill the existing national data gap, facilitate analyses of building embodied footprints mitigation strategies, and contribute to complete building life-cycle impacts studies.

1. Introduction

China's rapid economic and social development has generated huge demand for buildings. Due to accompanying rapid urbanization, over 2 billion square meters (m^2) of residential buildings have been built annually since 2009 (NBSC, 2013), approximately eight times larger when compared to the United States (USCB, 2014). China's recently booming economy drives the construction of offices, plants and warehouses, restaurants, and hotels, and the country's rising middle class and ongoing development of a better-off society have also created vigorous markets for entertainment, educational, and healthcare buildings. Understanding the embodied air pollutant emissions and water footprints of different buildings is much in need and contributes to governmental authorities' robust policies to promote the country's sustainable urbanization. However, embodied emissions and water footprints data by building type are lacking in China.

Compared to other products such as food and steel, completely quantifying the air pollutant emissions and water footprints of buildings is difficult. Building construction is supported by complex supply chains involving many manufacturing sectors in the economy, such as cement production, steel rolling, and pottery and porcelain manufacturing (Chang et al., 2013). Moreover, the upstream (earlier-stage) production of each material in an economy has "ripple" effects, i.e., the supply chain sectors of each material can always be traced back to their upstream sectors due to sectoral correlations in the economic system. This complicates the complete system boundary definition for building embodied footprints calculation. In addition, buildings can be of multiple types with various structural and architectural designs and material selections, and this results in different supply chain inputs (Chang et al., 2012).

Derived from the economic input–output technique developed by Leontief (1936, 1970), the input–output life cycle inventory (I–O

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LCI) approach enables comprehensive quantification for the energy and environmental footprints of products and services through the integration of economy-wide sector correlations and sectoral energy and environmental intensities (that is, the energy consumption and air pollutant emissions of per-unit sectoral economic outputs) (Hendrickson et al., 2006). However, since the I–O LCI model uses sector-level data, the model application is seriously constrained by sector aggregations in the I–O table, where sectors of similar products production are usually grouped into one parent sector. As a result, the I–O LCI model yields national average supply chain purchase and energy and environmental footprints for a broad category of comparable products, and obscures the unique production process for individual products (Suh and Nakamura, 2007). In terms of the Chinese I–O table, all types of building (e.g., residential building, office building, and educational building) and civil engineering products (e.g., road, railway, and bridge) are grouped into one construction sector. Therefore, existing studies (Chang et al., 2013; He et al., 2013) had no choice but to adopt this highly aggregated IO model for building embodied energy and emissions quantification, bringing uncertainty to study results.

Sector disaggregation provides the solution to the aggregation drawback of the I–O LCI model and enables the model to be applicable to more specific product types (Hendrickson et al., 1998). The methodology and procedures of the I–O LCI model disaggregation have been illustrated in existing studies (Joshi, 1999; Lindner et al., 2013; Chang et al., 2014; Algarin et al., 2015). For construction products in China, the construction sector in the Chinese I–O table is highly aggregated, including civil engineering construction, building construction, installation, decoration, and others (building repair, sub-contract management, etc.). The sector's products are civil engineering projects and buildings (Chang et al., 2014), see Fig. 1. Such highly aggregated construction sectors in China's I–O table prevents the I–O LCI model from distinguishing different buildings and calculating respectively their embodied energy and environmental footprints, and thus prevents full understanding of the environmental and resource burdens associated with the country's rapid urbanization.

Therefore, this study aims to address the aforementioned knowledge barrier by estimating the embodied air pollutant emissions and water footprints for different buildings in China. The earlier developed disaggregated I–O LCI model was employed (Chang et al., 2014), which divides the construction sector in the Chinese I–O table into 13 building sub-sectors. To our knowledge, our paper presents the first building embodied impacts quantification using a disaggregated I–O LCI model, addressing the highly aggregated construction sector in China's economic systems and enabling complete yet specific understanding of building embodied footprints in the country. Given that the disaggregated I–O LCI model presents national scale quantification, results of this study could be used by governmental authorities to expediently estimate the environmental emissions and water consumption associated with China's rapid urbanization, by policy-makers to identify and regulate the building supply chain sectors with significant environmental and resource footprints, and by the life cycle assessment (LCA) community to conduct LCA studies for more building types using hybrid LCI approaches. It should be clarified that the methodology and procedure of the disaggregated I–O LCI model development have been completely illustrated in a previous study (Chang et al., 2014), and the present study focuses on the model's application to building embodied air pollutant emissions and water footprints quantification. The "cradle to gate" system boundary of this study excludes building operations and demolition because China is experiencing a rapid urbanization, and the embodied footprints of different buildings are instructive for government's policy management. Furthermore, given that the lifespan and operationally environmental intensity (emissions per unit building floor area) of different buildings significantly vary and the function of different buildings lacks comparability, estimating the emissions and water footprints for building operation are uncertain. However, the results of this study facilitate a complete building life cycle study when more reliable and specific data become available. And the life-cycle impacts of different buildings are contributing to robust decision-making related to sustainable urbanization in China.

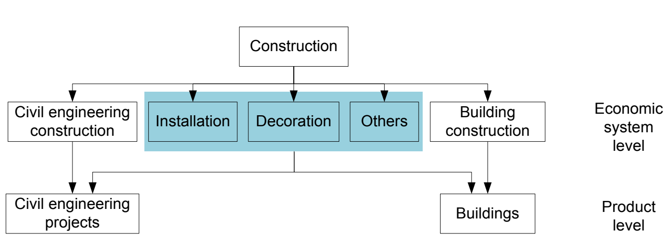

Fig. 1. Composition of construction sector in China's input–output table.

2. I–O LCI model

The basis for an I–O LCI model is the input–output technique developed by Leontief (1936, 1970). Through recording and analyzing the sectoral transactions in a society, the structure and operational state of its economic system is revealed. For the final demand of a given sector y, the economic outputs x of its correlated sectors can be calculated with the aid of the technical matrix. Such a method yields the "total supply chain" economic outputs of this sector throughout the economic system, see Formula (1).

$$x = [I - A]^{-1} y \tag{1}$$

where I is the identity matrix, and A is the technical matrix of all sectors.

Since x contains all output produced (direct and indirect), the external energy and emission function per economic unit of output can be used for calculating the overall environmental footprints for a given amount of output produced by summing across the impacts generated by each sector's production (Hendrickson et al., 2006), see Formula (2).

$$f = Ex = E[I - A]^{-1} y \tag{2}$$

where f is the embodied footprints for the final demand of a given sector y, and E is the environmental emission intensity (emissions per unit sectoral monetary output) matrix, which is also called the satellite matrix (Heijungs and Suh, 2002).

The number of sectors in an I–O table varies from country to country, and the sector classification determines the specificity of the scope of the sectors in the I–O LCI model. In general, the I–O LCI model when based on a more specific sector classification is capable of analyzing more products. However, since compiling an I–O table product-by-product is time and labor intensive, products with similar manufacturing processes are usually grouped in one sector in the national accounts. This is called sector aggregation. As a result, the aggregated sector would need to be disaggregated when calculating the embodied environmental footprints of a specific product. Otherwise, the results of the I–O LCI model are the average values for the sector. The sectoral aggregation problems in an I–O LCI model and relevant sectoral disaggregation approaches have been completely illustrated by Joshi (1999). For disaggregating an existing sector, say sector n, in a m-sector I–O table, the product