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Life-cycle carbon emission assessment and permit allocation methods: A multi-region case study of China's construction sector

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ABSTRACT

China is making efforts to reduce carbon emissions from the building industry, and carrying out an allocation and trading system for building emissions. However, to date, methods for using existing statistical data to assess the emissions of the construction sector and to make decisions affecting permit allocation are still unclear. In this context, a process is proposed in this study to calculate the life-cycle emissions of regional construction sectors in China, and a multi-criteria Gini coefficient is introduced as an indicator for emission permit allocation. Statistical data of the construction sector for 2004–2013 were analyzed. The results indicated an overall trend of increased emissions from China's construction sector, of which the production phase of buildings was shown to be the largest contributor. Various characteristics for different life-cycle sub-processes were also discussed at the provincial level. Finally, a case study of emissions from the construction sector was conducted on the basis of a multi-criteria Gini coefficient. Relevant analyses revealed the major regions in carbon reduction practices from a comprehensive view of efficiency and equality. In addition, suggestions were provided for allocating emissions for regional construction sectors. Overall, the present study would be helpful in the calculation, assessment, and allocation of emissions from China's construction sector. It should also provide insight into decision-making about low-carbon development policy of the building industry.

1. Introduction

The issue of global climate change has attracted increasing attention in recent years, because of its serious consequences to the natural and human environments (IPCC AR5, 2014). The construction sector accounts for nearly 36% of the worldwide carbon emissions (Chau et al., 2012), of which building operation is regarded as the main source in developed countries (Nässén et al., 2007; Onat et al., 2014). However, in tandem with the projected development of China's economy and urbanization, nearly 1.5 billion square meters of new buildings are being constructed annually according to the *China Statistical Yearbook* (National Bureau of Statistics, 2005b). This results in a dramatic growth of CO_{2e} (carbon dioxide equivalent) emissions from construction works. Consequently, both production and use phases of buildings are crucial factors for China's low-carbon development as promised at the United Nations Climate Change Conference (Gong et al., 2012).

The process method and input-output analysis (IOA) are two essential approaches for carbon emission analysis (Huang et al., 2009). For micro-level research relevant to individual buildings, process-based analysis could achieve the desired level of details of a target process, and consequently is usually applied in life-cycle carbon assessments (LCCA). Various process-level studies pertaining to production of materials, on-site construction, building operation, demolition, and waste treatment were conducted by previous researchers (Biswas, 2014; Gustavsson and Joelsson, 2010; Li et al., 2013; Mahapatra, 2015; You et al., 2011). Overall, analytical methods for micro-level LCCA have been adequately investigated and reviewed (Abanda et al., 2013; Chau et al., 2015; Islam et al., 2015).

With respect to macro-level assessment, there is relatively less process-based research relevant to the carbon footprint of the building sector (Zhang and Wang, 2016b). For this, IOA is usually applied considering its advantages to account for entire supply chains. For example, Acquaye and Duffy (2010), Chang et al. (2016), and Nässén et al. (2007) analyzed the embodied emissions of the Swedish, Irish, and Chinese construction sectors, respectively. Onat et al. (2014) investigated the life-cycle emissions of U.S. buildings,

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dividing the emission sources into three scopes. However, IOA has certain limitations for carbon assessment. First, IO tables in China are formally updated every five years. Second, converting monetary values to emissions could introduce inevitable uncertainties. Finally, the desired level of detail might not be achievable based on the statistical data available for the specified analysis of building sector.

As the largest emitter of GHGs (greenhouse gases) (Zhang et al., 2014a,b), China is making great efforts to control its emissions. Recently, an allocation and trading system for carbon emission permits (CEP) is being created for industrial producers (e.g., steel and cement plants) to encourage low-carbon techniques (Xiong et al., 2015). Meanwhile, a similar system from the perspective of consumers might reduce the total material consumption and related emissions. Accordingly, CEP allocation for buildings, among the largest consumers of materials and energy, have also been discussed and tried out in Shenzhen, Shanghai, and other places in China (Zhao et al., 2016).

Although there have been attempts in previous studies to analyze provincial GHG emissions in China (Huang et al., 2015; Su and Ang, 2014; Tian et al., 2014; Wang et al., 2013), and permit allocation of national emissions among regions (Zhang et al., 2014a,b, 2016), research specifically relevant to multi-regional construction sectors, based on statistical data, are relatively few (Hong et al., 2016; Liu and Lin, 2016). However, such analyses were preconditions for studying emission characteristics and building up the allocation and trading system. In this context, CEP allocation for regional construction sectors is facing a great challenge considering the currently used principles (Zhang et al., 2015). On the other hand, once a statistically relevant method for determining carbon emissions of regional buildings is provided, the assessment of results becomes another key point. Gini coefficient was previously indicated as a practical indicator for the analysis of environmental issues, and could enable balance between efficiency and equality for permit distribution (Druckman and Jackson, 2008; Groot, 2010; Pilla et al., 2016; Liang et al., 2016; Sun et al., 2010; Wang et al., 2015; Xiao et al., 2012). China's building industry is involved in an ongoing low-carbon path to development, and compliance with different reduction targets should occur in various regions considering their social and economic background. In this context, a multi-criteria Gini that could balance these factors in allocating building carbon-emissions might be a possible approach, and would have potential advantages. Overall, the proposed Gini approach should offer new insight into the target decomposition of carbon reduction policy in the building industry.

With consideration of the above-mentioned knowledge gaps, the present study aimed to achieve the following: (1) propose a process-based approach for life-cycle carbon emission assessment of regional construction sectors in China, and (2) introduce an environmental Gini coefficient as an indicator for building carbon analysis and for permit allocation in multiple regions. Accordingly, the contributions of the study could be summarized from three aspects. First, proposal of relevant methods would be good practice for emission analysis of building life-cycles based on statistical data. Second, time-series emissions of the building sector in 30 regions (including 22 provinces, four autonomous regions, and four municipalities) of China from 2004 to 2013 would provide good knowledge of the current situation of regional building life-cycles. Finally, a case study of carbon permit allocation for regional building sectors would have potential application for decision-making about relevant carbon-reduction targets.

The remainder of the paper is organized as follows: Section 2 provides an introduction of the scope of research, analytical methods, and collection of data. In Section 3, the results of case studies are analyzed, and some policy implications are offered. Finally, in Section 4, the study is summarized and specific significance and limitations are presented.

2. Methodology

2.1. Research scope

In accordance with the life-cycle of individual buildings (Sandanayake et al., 2016), the life-cycle of the construction sector consisted of three fundamental components. First was the materialization stage (MAT): incorporating materials production, transportation, and on-site construction of new buildings. Second was the operation stage (OPE): the daily operation of existing buildings. Third and last, was the disposal stage (DIS): demolition of buildings no longer useful and related waste transportation. It should be emphasized that the "life-cycle" here pertains to the entire inventory of the construction sector based on annual statistical data, which is very different from that of an individual building (Onat et al., 2014).

The process-based approach was applied for the carbon emission assessment, and was primarily aimed at improving the details and accuracy of the analytical results. The essential concept of this technique can be explained as "$Emissions = EQ \times EF$" (Hong et al., 2016), where EQ and EF indicate the engineering quantities and associated emission factors, respectively. Accordingly, carbon emissions of the six sub-processes involved in the three life-cycle stages could be evaluated, with further consideration of the various characteristics of statistical data relevant to each process.

2.2. Life-cycle carbon emission assessment of construction sector

2.2.1. Carbon emissions from the materialization stage

Regarding the production of materials, process-based emissions can be calculated as follows:

$$E_{pro} = \sum_{s=1}^{n} \left(m_s \times EF_{pro,s} \right) \tag{1}$$

where E_{pro} represents the emissions from production of materials, n is the total number of material types, and m_s and $EF_{pro,s}$ are the quantity and CO_{2e} emission factor of type s material, respectively.

In light of the details and availability of data, five kinds of materials (steel, cement, wood, glass, and aluminum) were considered in the present study. Relevant consumption data for regional building sectors were obtained from the *"China Statistical Yearbook on Construction"* (National Bureau of Statistics, 2005c). However, in consideration of the existence of double counting and possible errors in statistical quantities, certain modifications were made based on previous research (Lin et al., 2015). Furthermore, an accessional 10% of the emissions from the above primary materials were added, assumed to be the emissions of "others".

For building-materials transportation, fuel combustion is the most pertinent source of emissions, and was estimated by:

$$E_{tran} = \sum_{r=1}^{3} \sum_{s=1}^{n} \left(Wd_{sr} \times EF_{tran,r} \right) \tag{2}$$

where E_{tran} represents the emissions from transportation, Wd_{sr} is the freight turnover (material weight multiplied by transport distance) of type s material transported via method r, and $EF_{tran,r}$ is the emission factor of the transport method r. Here, Wd_{sr} was calculated based on the above materials consumption, and the average transport distance was deduced from National Bureau of Statistics, 2005b and the *"Yearbook of China Transportation & Communications"* (Association of China Transportation and Communications, 2016). The three main methods of transportation considered were railway,