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Quantifying city-scale carbon emissions of the construction sector based on multi-regional input-output analysis

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Abstract

Cities and metropolitan regions are open systems that rely heavily on external trade and release carbon dioxide (CO_2) as a predominant by-product. Quantification of trans-boundary emissions is essential, especially for the construction sector, which requires great intermediate inputs from upstream sectors locally and globally. This study investigates the global energy-related CO_2 emissions induced by Hong Kong's construction final demand based on multi-regional input-output analysis for the years 2004, 2007, and 2011. The results showed that consumption-based CO_2 has slightly declined from 2004 to 2007. This trend was closely tied to decreasing emission intensities of upstream sectors, even with strong growth in construction final demand volume. The total consumption-based CO_2 emissions from the construction sector were 10.19 Mt that suppressed 7.70 Mt production-based emissions in 2011. The discrepancy between these two emissions decreased from 85% to 32% over the study period, largely owing to the decline in emission intensities of cross-boundary Manufacturing and Utilities sectors. 96.61%-97.41% of total consumption-based CO_2 were indirect emissions, and 73.50%-78.58% were trans-boundary emissions. Utilities, Manufacturing, and Transport & Storage were the main source sectors contributing the most to total CO_2 emissions. Based on the results, extended emission monitoring beyond municipal boundaries, collaborative mitigation strategies with other cities and regions, and use of low carbon-intensive building materials locally and from nearby regions are proposed to mitigate construction-related CO_2 emissions.

Keywords: CO_2 emissions, construction sector, multi-regional input-output analysis, urban area

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Introduction

Mitigation policies for greenhouse gas (GHG) emissions related to the built environment have received more attention (Huang et al., 2018). Global energy-related carbon dioxide (CO_2) emissions reached a historic high of 32.5 Gt in 2017 (IEA, 2018). Buildings and construction sector are responsible for 39%—28% from building facilities and operations, and 11% from building materials, transport, and construction activities—of energy-related CO_2 emissions in 2016 (UNEP, 2017). Energy demand and related emissions from the built environment will continue to rise, driven by rapid growth in population, residential and services floor area, and demand for innovative products and energy-consuming devices (IEA, 2013). Moreover, accelerated international trade and globalization are intensifying the geographical fragmentation of production (Fujita and Thisse, 2006), and also generating CO_2 emissions from transport and industrial activities (Huwart and Verdier, 2013). The energy and materials consumed in construction projects located in one region might originate from various regions as the international fragmentation has increasingly split up the processes of production, distribution, and consumption. It is vital to understand the direct and indirect CO_2 emissions generated by the construction sector at the global level, especially for the emissions embodied in trade (EET). Proper measures and mitigation policies could then be formulated for both local and global carbon emissions.

The importance of cities and metropolitan regions in the global supply chain has been acknowledged as the economic performance of a nation increasingly relies on its city-regions (McCann and Acs, 2011). At the same time, those urban areas are claimed to be responsible for more than 75% of global energy-related GHG emissions (UNEP, 2014). In spite of many studies on urban emissions, much less is known about leakage of CO_2 emissions from construction activities through trade with other regions. As one of the leading financial hubs, Hong Kong is used as a case study to explore changes in city-scale CO_2 emissions from the construction sector over a period of time. The objective of this study is to quantify the CO_2 emissions generated by Hong Kong's construction sector with a time series approach, and to identify the composition of direct, indirect, and imported emissions with a trans-boundary approach.

Literature Review

Previous studies have attempted to quantify GHG emissions generated by the construction sector at the macro-level. Input-output analysis (IOA) and input-output life cycle assessment (IO-LCA) are commonly used methods. Huang et al. (2018) conducted IOA and found that 23% of global CO_2 emissions are from the construction sector, and 94% of the construction-related emissions are indirect emissions. Chen et al. (2017b), and Chuai et al. (2015) used IOA to investigate the composition of CO_2 emissions emitted by the Chinese construction sector. Both papers suggested the indirect emissions represent over 95% of total emissions. Hong et al. (2013) conducted process-based LCA and IO-LCA approaches and stated material production, transport, and on-site activities are responsible for 95.2%, 1.8% and 3.0% of global warming potential. Huang and Bohne (2012) applied IOA to conclude that an increasing trend in GHG emissions is observed in the Norwegian construction sector from 2003 to 2007, but with decreasing emission intensities. Chang et al. (2010) performed IO-LCA to reveal that the embodied energy and environmental emissions of the Chinese construction sector have gradually increased from 2002 to 2007. Nässén et al. (2007) also applied IO-LCA to quantify the CO_2 emissions from the Swedish building sector. Their results indicated the direct, indirect, and imported emissions account for 23%, 46%, and 31% of total emissions, respectively. Similar findings were reported by Acquaye and Duffy (2010) using IOA, with the share of direct, indirect and imported emissions at 17%, 41%, and 42% respectively in the case of Ireland's construction sector. CO_2 is concluded to be the most dominant emission, with negligible contributions from N_2O and CH_4.

These studies provide several key insights. (1) Although the level of GHG emissions in the construction sector has increased, the emission intensities have been steady or decreased over time. Those intensities in the developing counties are larger than the values in the developed counties. (2) Emissions generated are dominated by CO_2. (3) Indirect emissions are by far the greatest contributor, ranging from 77% to 95% of total emissions. Yet, the issue of emission leakage is less discussed in these studies. Inattention to environmental pollution through international and interregional trade could result in delivering insufficient information on consumption patterns at the regional and sectoral level. Suboptimal policies and strategies for the construction sector may be formulated in the absence of relevant information (Hong et al., 2016).

Under the accounting rule of the Intergovernmental Panel on Climate Change (IPCC) guidelines, national GHG emissions refer to the emissions that are released from production and consumption processes within the territorial areas of a nation (IPCC, 2006). This production-based accounting (PBA) framework is built on the concept that the producer should be responsible for the emissions released. With the ongoing wave of specialization and globalization, production supply chains are now spanning several economies or even regions. The observed emission stabilization in developed economies was more or less related to growing imports from developing economies (Davis and Caldeira, 2010; Peters et al., 2011a). The absence of emissions embodied in international trade may underrate the responsibility of an open economy which exports less than it imports. According to Peters et al. (2011a), the CO_2 emissions embodied in trade among 113 economies has reached 7.8 Gt (26% of global emissions) in 2008.

Consumption-based accounting (CBA) is offered as an alternative approach that attributes the emitted emissions along the supply chains and distributions to the final users (Munksgaard and Pedersen, 2001; Peters and Hertwich, 2008; Wiedmann, 2009). The consumption-based emissions are often referred to as carbon footprints (Steininger et al., 2018). PBA and CBA approaches complement each other to fulfil the following purposes: (1) reveal different pictures as producer and consumer for an economy; (2) demonstrate the effects of trade on its emission budget (Wiedmann, 2009; Steininger et al., 2018); (3) allocate carbon flows of products and services (Hu, et al., 2016); and (4) identify structural shifts in consumption patterns (Hertwich and Peters, 2009; Baiocchi and Minx, 2010). The outcome difference between the two methods is associated with EET, including international transport (Peters, 2008; Peters et al., 2011a).

There are several approaches to quantifying the emissions embodied in production, consumption and international trade (Kanemoto et al., 2011; Sato, 2014; Zhang et al., 2017). Considering the complexity of trade transactions, with the associated economic and environmental data, environmentally extended multi-regional IOA (MRIOA) has been used intensively with well-established methodologies and robust databases (Wiedmann, 2009; Arto et al., 2014; Steininger et al., 2018). Numerous papers have applied MRIOA to cover the global economy in estimating GHG emissions and carbon linkage (Peter and Herwich, 2008; Herwich and Peter, 2009; Wilting and Vringer, 2009; Davis and Caldeira, 2010; Peters et al., 2011a; Wiebe et al., 2012). Other empirical studies have emphasized carbon footprints at the national level through a time-series of multi-regional input-output tables (MRIOTs), such as for Austria (Muñoz and Steininger, 2010; Steininger et al., 2018), China (Fan et al., 2016; Mi et al., 2017), EU-countries (Kanemoto et al., 2016), Japan (Kanemoto and Tonooka, 2009; Kanemoto et al., 2016), the UK (Baiocchi and Minx, 2010; Wiedmann et al., 2010) and the US (Weber and Matthews, 2007; Fan et al., 2016). Several key findings shared across these studies are summarized as follows. (1) There is an increased leakage of GHG emissions from developed economies to developing economies through international trade. Most of the developed economies are recognized as net importers of embodied emissions except for the ones with larger exports of natural resources. (2) Small and trade-exposed economies tend to have a higher value of emissions embodied in imports (EEI) than large and diversified economies. (3) Construction activities account for 10% of GHG emissions globally. GHG emissions at the sectoral level were much less emphasized, and often found as part of a national analysis in MRIOA studies. The construction sector is frequently quantified as one of the significant contributors of consumption-based emissions (Hertwich and Peters, 2009; Muñoz and Steininger, 2010; Liu et al., 2015; Steininger et al., 2018).

A growing body of literature discusses environmental impacts at the urban level due to an increasing recognition of the importance of local action in climate change mitigation (Minx et al., 2013), and the nature of urban areas. Cities and metropolitan regions are open systems that rely heavily on the outside world to acquire materials and release wastes. GHG emissions are a prominent example of the urban by-products (Bai, 2007). Recent urban studies that have focused on the CBA suggest that consumption-based emissions exceed production-based emissions in most urban areas, mainly located in developed countries, and some are reported in China. Several metropolitan areas are identified to be net importers of embodied GHG emissions, for example, Belgium (77% of GHG emissions are EEI) in 2007 (Athanassiadis et al., 2018), Sydney (71%) and Melbourne (55%) in 2009 (Chen et al., 2017a), Xiamen City (59%) in 2010 (Lin et al., 2015), and Tokyo (53%) in 2011 (Long and Yoshida, 2018).

Some MRIOA studies have expanded the scope to compare the GHG emissions for a series of urban areas. Minx et al. (2013) studied the carbon footprints of 434 municipalities in the UK. Their results showed that 90% of municipalities are net importers of embodied CO_2 emissions, while the averaged carbon footprint of urban areas is lower than that of rural areas. As in China, Feng et al. (2014) reported that over 70% of emissions consumed in the three largest urban areas—Beijing, Shanghai, and Tianjin—are imported from other regions in 2007. The dominant share of EEI is attributed to the construction sector, owing to the continuous demands for urban capital investments. Sudmant et al. (2018) compared the emissions of 45 urban areas in China, the UK, and the US. The results indicated that income level and population density are strong predictors of consumption-based emissions. Higher income levels lead to greater emissions from increasing demand which is usually met by imports.

Methods and Data

Study Framework

Hong Kong is selected in the study to represent an urban economy which is regarded as open and highly externally oriented (Rao and Singh 2010). Its high dependence on external trade with the relocation of manufacturing operations to South China has led to a service-based economy. The share of services comprised 92.7% of the GDP, whereas the manufacturing share of GDP fell to 1.1% in 2015 (Census and Statistics Dept., 2017). The extensive use of imported goods with the skewed economic structure has expected to change the trading behaviors and production processes of the local construction activities, thus altering CO_2 emission flows. Turner et al. (2007) pointed out that MRIOA is an appropriate framework for allocating the total (direct plus indirect) pollution embodiments of final consumption, given this framework's consideration on the interdependence between sectoral activities within an economy. An MRIOA of Hong Kong is conducted in this study to analyze CO_2 emission flows generated by the construction sector along the global supply chain.

Within this MRIO framework, supply chains to/from Hong Kong arise from three geographical regions, including Hong Kong (H), China (C) and the rest of world (R, or denoted as RoW). These three regions are assigned to represent the city, national, and global scales, respectively. An MRIOT framework with *n* sectors that defines the transaction flows and embodied emission flows related to Hong Kong is depicted in Figure 1. The concepts and methods used in the compilation of environmental extended IOA and MRIOA are given in detail in Miller and Blair (2009), Turner et al. (2007), and Hermannsson and McIntyre (2014).

<Please insert Figure 1>

Accounting Framework and Data

The basic principle of environmental extended IOA is that the impacts or emissions associated with intersectoral production are generated in response to final demand within an economy (Miller and Blair, 2009). For a single-region economy in an IOA framework, the economic output is determined as:

$$x^{r} = A^{rr} x^{r} + y^{rr} + y^{r*} \quad (1)$$

and the total impacts or emissions are calculated based on Eq.(1):

$$f^{r} = F^{r} x^{r} = [F^{r} \, (I - A^{rr})^{-1}](\, y^{rr} + y^{r*}) \quad (2)$$

where x^{r} is the vector of total sectoral output, $\mathbf{A^{rr}}$ is a matrix of intermediate demand with each element (a_{ij}) revealing the sectoral inputs from sector i to sector j to produce one unit of output for the latter sector, and $A^{rr}x^{r}$ is the vector of total intermediate demand. y^{rr} is a vector with elements indicating the domestic final demand in each sector in region r, and y^{r*} represents the total exports from region r to other regions. Imports are generally excluded in the framework (Peters, 2008). f^{r} denotes total domestic emissions generated by all production activities in response to domestic consumption (y^{rr}) and exports (y^{r*}). F^{r} is a vector with vector elements representing the average generation of emissions per unit of sector output (referred to as direct emission intensity). $\mathbf{I}$ is the identity matrix. The matrix $\mathbf{(I - A^{rr})^{-1}}$ is known as the Leontief inverse with elements (b_{ij}) describing the amount of output generated in sector i for one unit change in final demand of the sector j. The column sum in the Leontief inverse matrix is known as an output multiplier that depicts the impact of an increase in final demand for sector j upon all sectors within the economy. A vector of total emission intensities is bracketed in Eqs.(2). The elements in that vector represent the total direct and indirect emissions generated along supply chains to satisfy a unit increase in the final demand of each sector.

There are two main categories of household emissions. One is the emissions embodied in products and services, and those can be derived from Eqs.(2). The other is the direct emissions that arisen from household activities, for example, combusting transport fuels. Both two emissions should be included to complete the impact estimation. Hence Eqs.(2) is extended to include the direct emissions of household activities.

$$f_t^r = F^r x^r = F^r \, (I - A^{rr})^{-1} (y^{rr} + y^{r*}) + f_{hh}^r \tag{3}$$

where f_{hh}^r is the total direct emissions of household activities. It can be derived from multiplying the direct emission intensity of household (F_{hh}^r) with the level of household final demand (y_{hh}^r).

A 3-region MRIOT indicating the interregional transactions between Hong Kong, China and RoW is constructed in Figure 1. The diagonal blocks in the MRIOT represent the domestic IOTs (i.e. $\mathbf{Z^{HH}}$ for Hong Kong). The off-diagonal blocks (i.e. $\mathbf{Z^{CH}}$) show the intermediate requirements of imported products from one region (China) to the other region (Hong Kong). Exposition of the extension of the standard single-region framework in Eqs.(3) is applied to the 3-region framework and shown in matrix form.

$$\begin{pmatrix} f^{\mathrm{HH}} & f^{\mathrm{HC}} & f^{\mathrm{HR}} \\ f^{\mathrm{CH}} & f^{\mathrm{CC}} & f^{\mathrm{CR}} \\ f^{\mathrm{RH}} & f^{\mathrm{RC}} & f^{\mathrm{RR}} \end{pmatrix} = \begin{pmatrix} \mathbf{F^H} & 0 & 0 \\ 0 & \mathbf{F^C} & 0 \\ 0 & 0 & \mathbf{F^R} \end{pmatrix} \begin{pmatrix} \mathbf{I-A^{HH}} & \mathbf{-A^{HC}} & \mathbf{-A^{HR}} \\ \mathbf{-A^{CH}} & \mathbf{I-A^{CC}} & \mathbf{-A^{CR}} \\ \mathbf{-A^{RH}} & \mathbf{-A^{CR}} & \mathbf{I-A^{RR}} \end{pmatrix}^{-1} \begin{pmatrix} \mathbf{y^{HH}} & \mathbf{y^{HC}} & \mathbf{y^{HR}} \\ \mathbf{y^{CH}} & \mathbf{y^{CC}} & \mathbf{y^{CR}} \\ \mathbf{y^{RH}} & \mathbf{y^{RC}} & \mathbf{y^{RR}} \end{pmatrix}$$

$$+ \begin{pmatrix} f_{\mathrm{hh}}^{\mathrm{HH}} & f_{\mathrm{hh}}^{\mathrm{HC}} & f_{\mathrm{hh}}^{\mathrm{HR}} \\ f_{\mathrm{hh}}^{\mathrm{CH}} & f_{\mathrm{hh}}^{\mathrm{CC}} & f_{\mathrm{hh}}^{\mathrm{CR}} \\ f_{\mathrm{hh}}^{\mathrm{RH}} & f_{\mathrm{hh}}^{\mathrm{RC}} & f_{\mathrm{hh}}^{\mathrm{RR}} \end{pmatrix} \tag{4}$$

where f^{HH} denotes the total emissions generated by production activities in Hong Kong to support the local final demand, while f^{CH} is the emissions embodied in China-Hong Kong trade in response to the consumption in Hong Kong. In that sense, the emissions are allocated to the region of final consumption. For example, the consumption-based emissions of Hong Kong are the emissions incurred from domestic production and imported goods according to local consumption.

$$f_{\mathrm{c}}^{\mathrm{H}} = f^{\mathrm{HH}} + [\, f^{\mathrm{CH}} + f^{\mathrm{RH}} \,] \tag{5}$$

where the sum of the values inside the bracket equal to total emissions embodied in imports and shown as f_{i}^{r} for region r.

Similarly, the production-based emissions of a region can be obtained by summing row values in the total emission matrix ($\boldsymbol{f}$). This allows assigning emissions to the resident regions that emit the emissions in production. The production-based emissions of Hong Kong can be derived from

$$f_{\mathrm{p}}^{\mathrm{H}} = f^{\mathrm{HH}} + [\, f^{\mathrm{HC}} + f^{\mathrm{HR}} \,] \tag{6}$$

where the amounts inside the bracket represent all emissions embodied in exports (EEE) and shown as f_{e}^{r} for region r. Here, exports include goods for both intermediate and final consumption from the domestic supply chain only. The relationship between production and consumption-based emissions for region r can be expressed as

$$f_{\mathrm{c}}^{\mathrm{r}} = f_{\mathrm{p}}^{\mathrm{r}} - f_{\mathrm{e}}^{r} + f_{\mathrm{i}}^{r} \tag{7}$$

In the absence of Hong Kong official input-output tables (IOTs), the data used in compiling Hong Kong MRIOTs were derived from the Global Trade Analysis Project (GTAP) database version 9a for the benchmark year 2004, 2007 and 2011 (Aguiar et al., 2016). GTAP contains balanced, harmonized data (Narayanan and Walmsley 2008; Peters et al., 2011b) and inclusive sets of accounts outlining the annual flows of goods and services with regional and sectoral details for 140 regions and 57 sectors (Aguiar et al. 2016). The data for the 140 regions were aggregated into the 3 regions as proposed (Hong Kong, China, and RoW), and the 57 sectors were also aggregated into 10 sectors to reflect the service-dominating economic structure of Hong Kong (Supplementary Table S1). The method of converting GTAP into an MRIOT is described in detail in Peters et al. (2011b), and Andrew and Peters (2013).

The CO_2 emissions extension data from GTAP was estimated based on the energy volume data compiled by the International Energy Agency (IEA) and only covers the CO_2 emissions from fossil fuel combustion (Peters et al., 2012). GTAP uses different assumptions from the IEA to convert energy into CO_2 emissions that are then modified to be consistent with the economic data in the GTAP database (Peters et al., 2012). Also, GTAP allocates international transport emissions (from bunker fuels) to the suppliers and not the consumers. If GTAP is used in analyzing consumption-based emissions, international transportation emissions might be incorrectly allocated especially for economies with large imports or exports (Peters et al., 2009; Peters et al., 2011b). Nevertheless, the GTAP database provides complete and consistent data on bilateral trade, intermediate and final consumption, and CO_2 emissions. It is regarded as one of the most commonly used databases in contemporary policy-related analyses (Arto et al., 2014).

Other uncertainties and limitations in IOA and MRIOA are stated in previous studies. Those include selection of datasets and emission satellite accounts (Peters, et al., 2012; Moran and Wood, 2014), different assumptions and approaches used in the datasets (Tukker and Dietzenbacher, 2013), and the sector aggregation effect (Steen-Olsen et al., 2014).

Results & Discussion

Hong Kong's CO_2 emissions

Results of the MRIOA revealed that Hong Kong is a net importer of emissions with 23.87 Mt net CO_2 emission inflows in 2011. It generated 80.94 Mt production-based CO_2 or 11.45 tons of CO_2

per capita. The level of emissions increased to 104.82 Mt CO_2 or 14.82 tons of CO_2 per capita from a CBA perspective. The emissions released by 10 classified sectors in 2011 are shown in Figure 2. The five top PBA sectoral sources were Manufacturing (27.37%), Wholesale & Retail Trade (23.74%), Transport & Storage (12.64%), Utilities (10.57%) and Construction (9.51%). The main CBA sectoral sources were the same as the listed PBA sectoral sources but in a slightly different order, with Transport & Storage falling to fifth place. These five sectors were responsible for more than 80% of total CO_2 inventories in both accounting approaches. In terms of trans-boundary trade, EEE accounted for 58.79% of production-based CO_2, while EEI equaled 88.23% of production-based CO_2 or 68.17% of consumption-based CO_2 in 2011.

<Please insert Figure 2>

During the period 2004-2011, EEI made up 68.17%-73.87% of consumption-based CO_2 of Hong Kong (Supplementary Table S2). The results are close to several studies, showing that 74% of consumption-based emissions come from EEI in Beijing, 72% in Shanghai (Feng et al, 2014), and 71% in Sydney (Chen et al., 2016; Chen et al., 2017a). A great portion of EEI originated from China (39.94%-52.81%) with the remaining 47.19%-60.06% of EEI coming from the RoW region. Considering the level of EEI upon the local final demand, the highest shares of imported emissions were induced from Manufacturing (54.30%-57.16%), Wholesale & Retail Trade (12.48%-13.84%), and Construction (10.16%-10.63%).

The share of emissions generated by the construction activities to the total urban emissions remained within a range of 9.02% to 9.99% for both PBA and CBA approaches over the considered period. This result echoes the findings of Hertwich and Peters (2009) that construction activities account for an average level of 10% of total GHG emissions from the 87 evaluated regions in 2001, though the same paper reported the share for Hong Kong's construction sector to be around 13%. In the final demand perspective, consumption-based emissions generated from Construction were largely attributed to capital investment, which represented more than 97.77% of its sectoral final demand

Table 1. outlines the level of emissions sourced from Construction in 2004, 2007, and 2011. The consumption-based CO_2 emissions fluctuated slightly over the considered period, but the production-based CO_2 emissions increased steadily from 6.22 Mt to 7.70 Mt with an average annual growth rate (AAGR) of 3.10%. In contrast, the transaction volume (intermediate and final consumptions) grew continuously with AAGRs of 5.97% and 5.98% under PBA and CBA approaches, respectively. This implies that the level of production-based CO_2 emissions is affected to some extent by the declining emission intensity of the local supply chain, while energy efficiency gains and/or production structure changes from China and the RoW region are the main drivers for the decreasing consumption-based CO_2 emissions. The emission intensities are explained in more detail in section 4.3. As a whole, the discrepancy between the two absolute emissions has been reduced during 2004-2011. The percentage of excess of consumption-based CO_2 over production-based CO_2 was around 32% in 2011, compared to the 85% difference in 2004.

<Please insert Table 1>

EET for Hong Kong's construction sector remained roughly stable from 12.80 Mt in 2004 to 12.49 Mt in 2011. Again, emissions embodied in exports and imports for Hong Kong's construction sector revealed two opposite trends. The level of EEI dropped from 9.04 Mt to 7.49 Mt with an AAGR of -2.65%, while EEE experienced steady growth with an AAGR of 4.16%. Given that the trade volumes for both exports and imports exhibited rapid growth with AAGRs of 7.30% for exports and 5.97% for imports, the decline in the emission intensities has contributed to a lower level of EEI and a slower growth rate of EEE.

Figure 3. presents changes in various economic and emission indicators from 2004 to 2011 and allows for comparing the relative performance of Construction and Hong Kong economy. For

Hong Kong, a slight decrease was observed in the level of EET and the level of consumption-based CO_2, as the trade and demand volume experienced strong growth from 2004 to 2011. That indicates that even with the strong growth of the urban final demand and trade volume, the EET level has remained stabilized, largely owing to the decreasing emission intensities. Similar trends were shown in the construction sector with the relatively greater discrepancy between production- and consumption-based emissions. The larger discrepancy was due to the higher share of EEI over total consumption-based emissions in the construction sector (73.50%-78.58%) than the Hong Kong average (68.17%-73.87%) (Supplementary Table S2). From the results, it is apparent that PBA and CBA offer complementary perspectives in understanding the local and sectoral responsibilities in CO_2 emissions. Allocation of consumption-based emission flow is essential to reveal the composition and source sectors of emissions as a consequence of the construction sector's final demand.

<Please insert Figure 3>

Breakdown of CO_2 emission flows induced by Construction

Figure 4. displays the emission origins induced by the final demand of Hong Kong's construction sector along the global supply chain for the years 2004, 2007, and 2011. Here the direct and indirect consumption-based CO_2 emissions are revealed. Direct emissions refer to those derived from on-site activities. Indirect emissions are those released in other sectors in providing products and services for construction operations. From 2004 to 2011, Hong Kong's construction sector was responsible for 9.78-11.50 Mt of CO_2 emissions, or 1.41-1.70 tons of CO_2 per capita. 2.59%-3.39% of total emissions were direct emissions, 18.83%-23.11% were indirect emissions from other sectors within Hong Kong, with 73.50%-78.58% came from EEI. Altogether, the top three source sectors that supported Hong Kong's construction consumption were Utilities (40.30%-41.24%),

Manufacturing (29.81%-32.76%), and Transport & Storage (20.88%-24.22%) across the world.

<Please insert Figure 4>

Previous studies have shown that over 94% of total CO_2 emissions generated by the construction sector are indirect emissions (Huang et al., 2018). The percentage is even higher in the case of China, ranging from 95.4% to 99.3% (Chang et al., 2010; Chuai et al., 2015; Chen et al., 2017b; Huang et al., 2018). The main source sectors are listed as ‘electricity, gas and water supply’, ‘non-metallic manufacturing’, ‘primary metal and fabricated metal manufacturing’, ‘mining’ and ‘transport, storage and information’ from 1995-2010 (Chuai et al., 2015; Chen et al., 2017b). The results are similar to those of Hong Kong, with Utilities and Manufacturing being the dominant contributors. Yet, the share of Transport & Storage is greater than the reported figures in China (within a range between 2.7% and 4.5%). The distant location from inland China and the high dependence on imported products are two possible explanations for the significant emissions caused by transport.

The local emissions (direct and indirect emissions in Hong Kong) induced by Construction final demand have witnessed a steady increase over time, from 2.46 Mt in 2004 to 2.70 Mt CO_2 emissions in 2011 with an AAGR of 1.34%. Transport & Storage was the leading source sector, and its share over the total emissions had increased from 8.74% in 2004 to 10.70% in 2011, followed by Utilities and Manufacturing with shares at 7.52% and 4.64%, respectively. Again, the results reveal the significance of transport in urban emissions. Kennedy et al. (2011) aimed to estimate the production-based plus trans-boundary emissions for cities and metropolitan regions and suggested that aviation and marine emissions should be included in urban emission to reflect the wider carbon dependence. The portion of transport emissions was proven to be substantial in urban emission inventories, for example, 40.5% in Barcelona, 32.3% in London, 6.8% and 6.1% in the cases of Shanghai and Tokyo.

Regarding trans-boundary emission inflows, the share of EEI experienced a slight decline over the considered period, decreasing from 78.58% to 73.50% from 2004 to 2011. Meanwhile, the emission volume dropped notably from 9.04 Mt in 2004 to 7.28 Mt in 2007, but climbed back to 7.49 Mt CO_2 emissions in 2011. The ratio of EEI found in the present study is higher compared to other research. The share of EEI was found to be 63% in Perth (Chen et al., 2016), and 42% and 31% for Irish and Swedish construction sectors, respectively (Nässén et al., 2007; Acquaye and Duffy, 2010). In general, China was the dominant contributor to Hong Kong's emission inflows, even as the share fell from 41.87% in 2004 to 30.50% in 2011. The downward volume and share of EEI from China are potentially due to the general decreasing emission intensity that is the result of the declines in the proportion of coal used in the energy sources, with improved energy use efficiency for industries in China (Chen et al., 2017b).

The ranking of the main source sectors for EEI remained roughly the same over the years, except for Manufacturing in China falling from second to fifth place. In 2011 the greatest source of EEI was Utilities in China (17.33%), followed by Utilities in RoW (15.45%), then Manufacturing in RoW (14.31%), Transport & Storage in Row (11.75%), and Manufacturing in China (10.86%). Emission inflows from Transport & Storage reached a high peak at 13.52% in 2011, especially from the RoW region. This increase is highly related to rapid growth of trade volumes (intermediate and final consumptions from RoW), which climbed up from 4.93 billion USD in 2004 to 7.75 billion USD in 2011 with an AAGR of 6.68%.

Sectoral emission intensities

Total emission intensity (F^r $(I–A^{rr})^{-1}$) is often used as a measure of the energy efficiency of a given sector, as it reflects product mix, production technology, sectoral structure, and pricing regime in the aggregated sectors (Peters and Hertwich, 2006). It is defined as the CO_2 emissions generated to satisfy a unitary final demand of a specific sector. As discussed in previous sections, consumption-based CO_2 induced by Hong Kong's construction final demand has witnessed a slight decline between 2004 and 2011, whereas construction final demand volume continued to expand at an AAGR of 6.01%. Here, direct emission intensity (F^r) and the total emission intensity of main source sectors are presented to depict the changes in emission intensities of the main source sectors over the examined period.

The decline in total emission intensity of Hong Kong's construction sector was mainly due to energy efficiency gains and not much from production structure changes. The economic influence of Construction in Hong Kong remained stable with output multiplier of 2.92 in 2004 to 2.93 in 2011, whereas 1.11-1.19 units leaked out through imports (Supplementary Table S3). 68.52% of the leakage was interconnected to manufacturing activities on average. While the composition structure and magnitude of Construction output multipliers stayed flat over time, the direct emission intensities of the main source sectors experienced a notable decline, as shown in Figure 5. The declining rates tended to be higher in China, followed by the RoW region and then Hong Kong. Taking Manufacturing as an example, the declining rates of direct emission intensities were 63.46% in China, 34.43% in RoW, and 14.47% in Hong Kong during the period (Supplementary Table S4). The energy efficiency improvements of Manufacturing and Utilities in China and the RoW region emerged from the data are claimed to be the dominant factor to offset CO_2 emissions generated by Hong Kong's construction sector, even with strong Construction final demand growth.

<Please insert Figure 5>

The total emission intensities for all sectors experienced a steady decline from 2004 to 2011. The rates of decrease vary within a range of 29.05% and 54.01% when compared to the 2004 level. Most of the cross-boundary sectors had higher total emission intensities than the local sectors, especially for energy-intensive sectors located in China, as illustrated in Figure 6. In addition, by comparing the direct and total emission intensities of Construction, a higher value in total emission intensity in Hong Kong (0.4 tonnes of CO_2 per thousand USD) was witnessed compared to that of RoW (0.2), but with a lower value in direct emission intensity (1.19E-02 tonnes of CO_2 per thousand USD) than RoW's (1.30E-02) in 2011. This observation aligns with local construction activities' heavy reliance on import products mainly from China, products that might be produced through a less energy efficient process. The less efficient manufacturing process and greater use of coal are claimed to be the reason (Chen et al., 2017b) for the greater relative total emission intensities of Chinese Manufacturing and Utilities sectors compared to those of the RoW region.

<Please insert Figure 6>

Policy implications

Hong Kong is recognized as a small open economy with few physical resources. The economy relies on significant quantities of imported goods and services to operate (Hung et al., 2019), but its GHG mitigation policies are based on the conventional PBA approach. The government is committed to reducing per capita emissions from 6.2 tonnes CO_2-e in 2014 down to 3.3-3.8 tonnes CO_2-e in 2030 (Environment Bureau, 2017). According to the results from Hong Kong MRIOA, the production-based emissions should be recalculated to become 10.17-11.45 tonnes per capita by including emissions from shipping and indirect intersectoral transaction flows. This figure climbed to 14.82-16.96 tonnes per capita when applying a CBA approach for the years 2004, 2007, and 2011. For cities or metropolitan areas that have a large discrepancy between the production- and consumption-based emissions, in addition to a high proportion of embodied emissions, should adopt a CBA approach in mitigation policy (Harris et al., 2012; Chan et al., 2016). Hence, consumption-based inventories should be employed in addition to production-based inventories in Hong Kong in formulating mitigation strategies. Recommended measures include extending the monitoring of CO_2 emissions along the supply networks beyond municipal boundaries. Information sharing and collaborative actions among cities or regions are advised since trans-boundary mitigation actions at a large scale are needed to stabilize or mitigate the GHG level.

The construction sector in Hong Kong contributed 4.43%-4.84% of total economic output in 2004, 2007, and 2011. Comparatively, construction activities are responsible for 9.78-11.50 Mt of CO_2 emissions, accounting for 9.46%-9.99% of total consumption-based urban emissions. It is worth noting that the reported emission volume represents the construction sector during a period of historically low output, with an average level of $13,080 million USD in 2000 prices. The construction output has increased to $19,117 million USD in 2017 with no provision for inflation (Census and Statistics Dept., 2018), and is projected to expand at an AAGR of 1.3% for the upper bound, or maintain its current level during the 2017 to 2026 period (CIC, 2018). This implies that the CO_2 emissions emitted by the construction sector will continue to increase gradually in the short term if emission intensities remain unaffected or decrease at a slower rate than that of final demand. Changes in product mix and production technology are required to mitigate the expansion of CO_2 emissions.

Building materials are responsible for the majority of embodied emissions from the construction sector (Giesekam et al., 2016, Huang et al., 2018). According to Hong Kong MRIOT data, the imports counted 42.25%-44.78% of intermediate input values for the construction sector. 87.38% to 91.06% of these imports were from cross-boundary manufacturing sectors. As a result, the production of building materials and machines abroad emitted 25.17%-29.46% of total construction-related CO_2 emissions. The development and use of less carbon-intensive building materials and energy efficient machines are encouraged. Moreover, CO_2 emissions caused by transport account for 20.88% to 24.22% of total CO_2 emissions during the period 2004-2011, largely owing to the increasing trade volume. To reduce the emissions from shipping, products can be imported from the Pearl River Delta, East Asia, and other nearby regions, rather than from other more distant economies.

Conclusions

Cities such as Hong Kong, with a skewed economic structure and few natural resources, depends largely on imported goods and services. Without sufficient information on CO_2 emission flows could lead to inefficient climate policies and actions in carbon mitigation. This study has explored the flow and composition of CO_2 emissions of the construction sector in Hong Kong from both PBA and CBA perspectives. A 3-region MRIO framework is used to illustrate the CO_2 emissions generated by Hong Kong's construction sector in 2004, 2007, and 2011. Findings are presented from four perspectives, namely, changes in CO_2 emissions by the construction sector over time, the variance between production- and consumption-based CO_2 emissions, the composition of direct and indirect CO_2 emissions, and contributions by source sectors to the total CO_2 emissions. Hong Kong is a net importer of emissions, with 23.87 Mt net CO_2 emission inflows in 2011, and its construction sector relying greatly on imports to meet the sectoral demand. The construction-related CO_2 emissions per capita were 10.17-11.45 tonnes from a PBA perspective, and the figure escalated to 14.82-16.96 tonnes per capita when considering a CBA approach for the years 2004, 2007, and 2011. The discrepancy between the production- and consumption-based emissions has decreased from 85% to 32% over the considered period, largely due to the declining emission intensities from cross-boundary Utilities and Manufacturing sectors. For the 9.78-11.50 Mt consumption-based CO_2 emissions induced by construction final demand, the indirect trans-boundary emissions accounted for 73.50%-78.58% from 2004 to 2011. Utilities (40.30%-41.24%), Manufacturing (29.81%-32.76%) and Transport & Storage (20.88%-24.22%) are the main source sectors contributing the most to the total CO_2 emissions. The decline in total emission intensity of

Hong Kong's construction sector from 2004 to 2011 is mainly due to energy efficiency gains from upstream sectors and not much from production structure change, especially for the manufacturing and utilities sectors located in China and the RoW region.

The findings reveal that the CO_2 emissions from Hong Kong's construction sector can be largely attributed to cross-boundary upstream sectors. Yet these indirect CO_2 emissions are currently left out of the practices and policy-making processes in Hong Kong. A CBA approach is advised to be adopted to more truthfully reveal the CO_2 emissions induced by local construction final demand. Mitigation strategies and emission monitoring should be extended beyond municipal boundaries. Information sharing and collaborative actions among cities or regions are advised. As Manufacturing and Transport & Storage sectors are responsible for over 50% of the total construction-related emissions, the development of the use of low carbon-intensive materials and energy efficient machines from Hong Kong and nearby regions are encouraged to reduce CO_2 emissions in the future.

This study focuses on analyzing CO_2 emissions induced by the final demand of Hong Kong's construction sector. Further studies can be extended by taking other GHG emissions into account. A finer level of geographical aggregation is recommended to assess the embodied emissions via national trade from major cities and provinces in China, as well as the embodied emissions via international trade from other world regions, such as Asia. Comparative analysis between urban areas can be extended to explore sectoral emissions in relation to other factors, such as geographical location, income level, and population density as well as import dependency. Information on the cost structure of major construction works should be included for further investigation, along with detailed analysis of imported building materials and trade pattern, to accurately identify the trans-boundary CO_2 emissions by considering the composition of construction deliverables.

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Fig. 1. Structure of a 3-region MRIOT

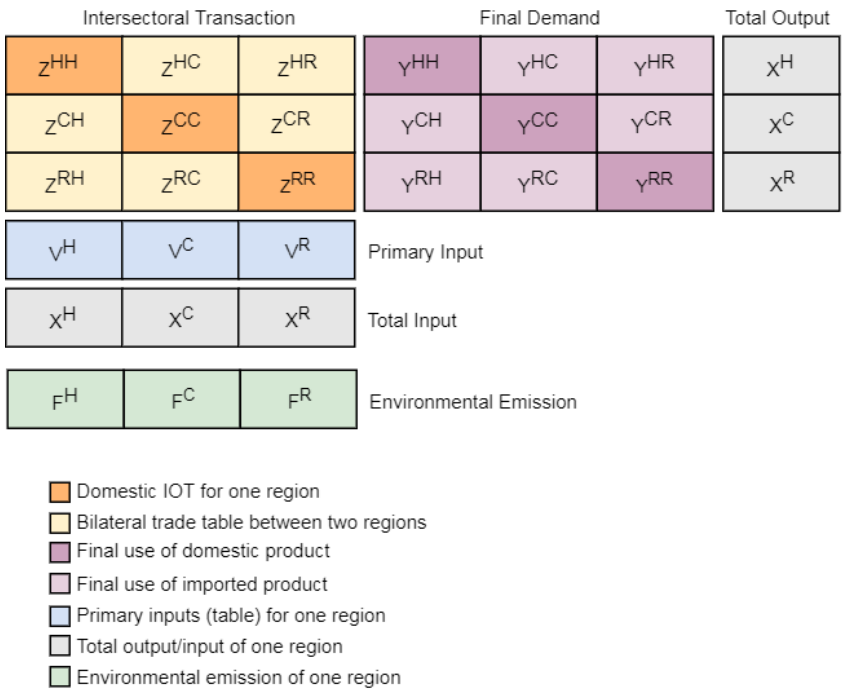
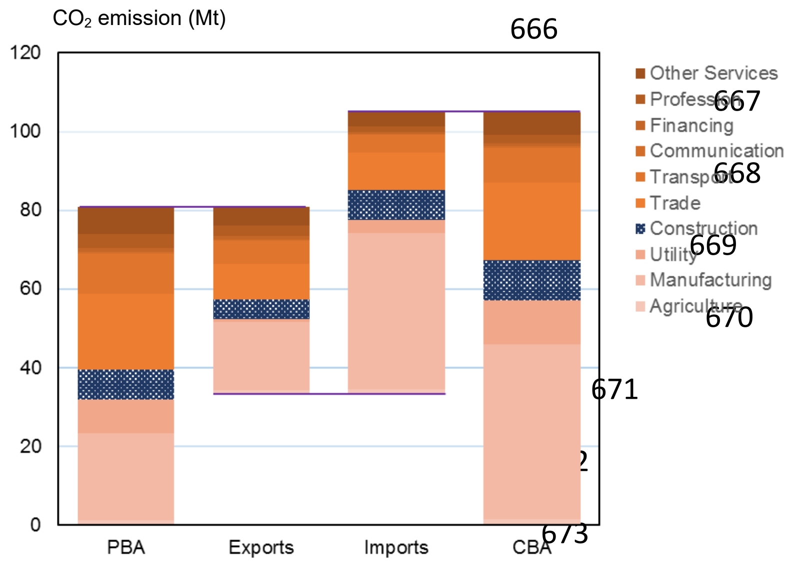


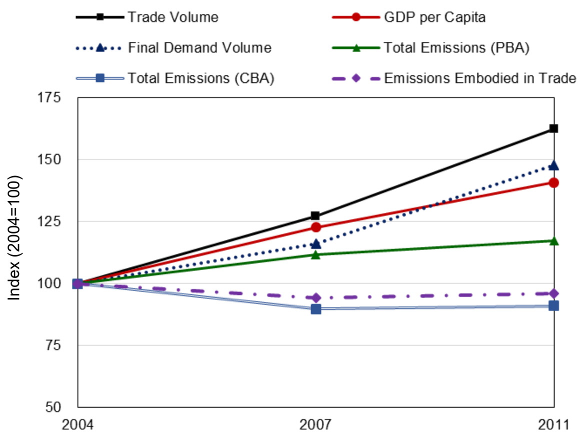
Fig. 2. Hong Kong sectoral emissions of production, exports, imports and consumption (2011)



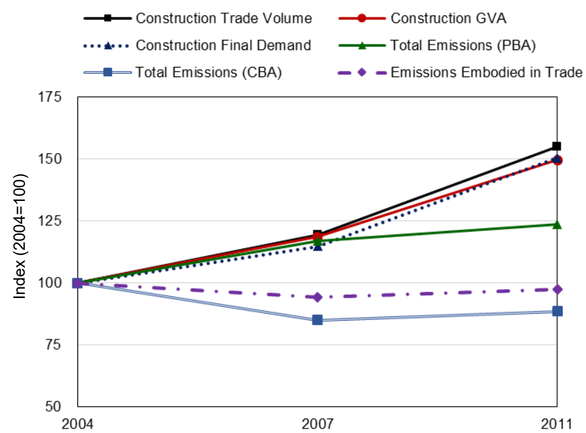
Note: Trade = Wholesale & Retail Trade; Transport = Transport & Storage; Communication = Information & Communication; Financial = Financing & Insurance; Profession = Professional & Support Activities.

Fig. 3. Indices of economic and emission indicators for Hong Kong

(a) Economy of Hong Kong



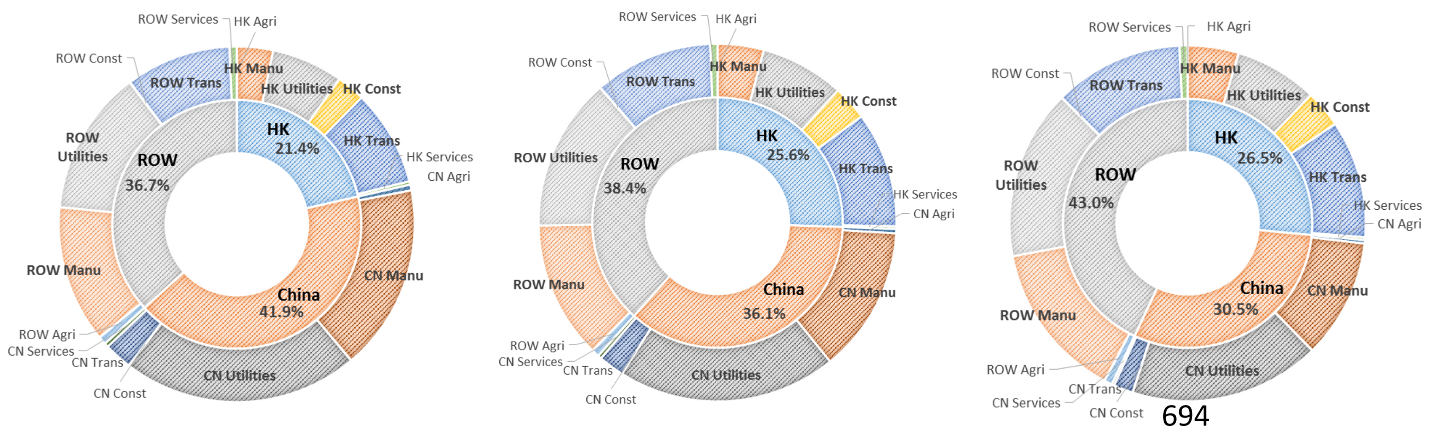
(b) Construction sector in Hong Kong



Note: Trade volume = the sum of imports and exports of goods and services for both final consumption and intermediate consumption; PBA = production-based accounting; CBA = consumption-based accounting; emissions embodied in trade = international transfers of CO_2 emissions from imports and exports; CBA emission intensity = ratio of consumption-based CO_2 emissions relative to regional (sectoral) output; GVA = gross value added.

Fig. 4. Composition of CO_2 emissions induced by Hong Kong's construction final demand

(a) Year 2004 (b) Year 2007 (c) Year 2011



Note: Agri = Agriculture; Manu = Manufacturing; Const = Construction; Trans = Transport & Storage; Services = all services sectors.

Fig. 5. Direct emission intensities of main source sectors (2004-2011)

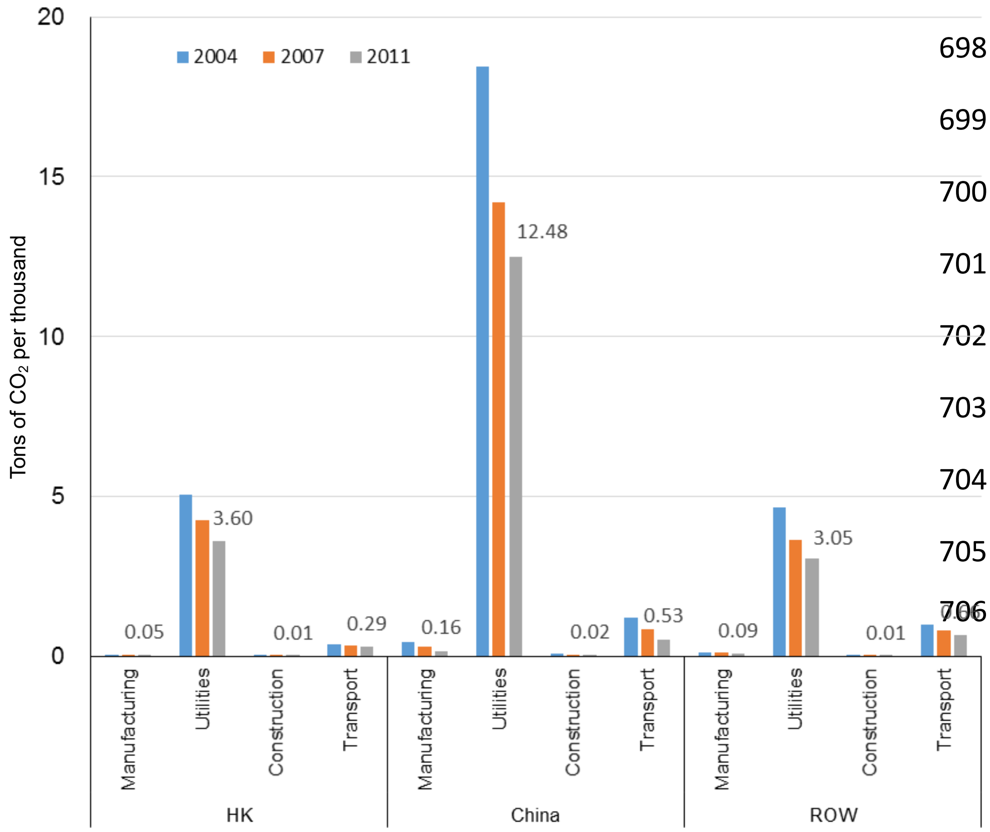


Fig. 6. Total emission intensities of main source sectors (2004-2011)

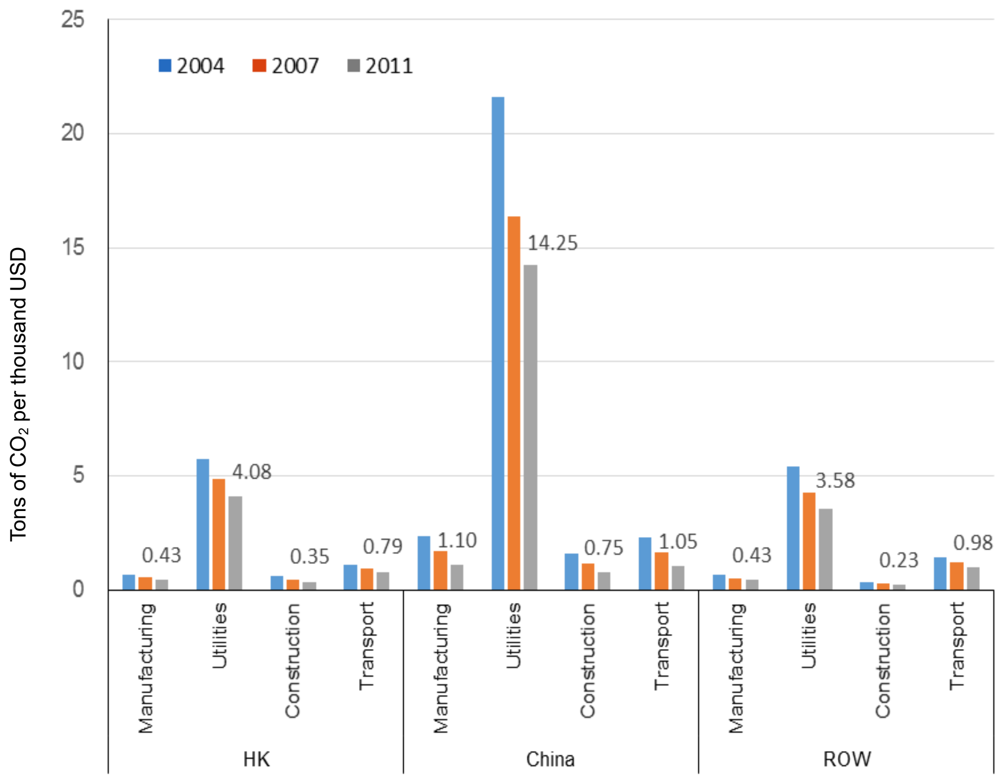


Table 1. CO_2 emissions by the Hong Kong's construction sector (2004-2011)

Categories	2004	2007	2011
Emissions embodied in trade (EET) (Mt)	12.80	12.07	12.49
Emissions embodied in exports (EEE) (Mt)	3.76	4.79	5.00
Emissions embodied in imports (EEI) (Mt)	9.04	7.28	7.49
PBA CO_2 emissions (Mt)	6.22	7.29	7.70
CBA CO_2 emissions (Mt)	11.50	9.78	10.19
CBA / PBA ratio	1.85	1.34	1.32

Note: EET = international transfers of CO_2 emissions from imports and exports = EEE+EEI.