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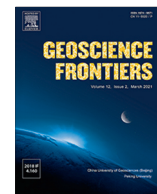
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Research Paper

Towards net zero carbon buildings: Accounting the building embodied carbon and life cycle-based policy design for Greater Bay Area, China

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ABSTRACT

Carbon mitigation of buildings is critical to promote a net-zero society. The international society has vigorously promoted “Net Zero Carbon Buildings” across the globe, and accounting for building carbon emissions is critical to support this initiative. Embodied carbon, which represents carbon emissions from the entire lifecycle of the buildings, is fundamental for realizing the idea of zero carbon. However, only limited studies have been conducted so far that take into account the city scale. This paper aimed to act as a first try to account for the embodied carbon emissions in buildings in 2020 for the Guangdong-Hong Kong Macau Greater Bay Area in China (GBA). We integrated remote sensing techniques such as night-time light data (NLT) and building material flows analysis to calculate and spatialize the newly generated building material stocks (MS). Based on the MS data, we further applied life cycle assessment (LCA) to assess the embodied carbon in the buildings. The results highlighted that over 163 million tons of embodied carbon in buildings of GBA are expected to be generated, from 497 million tons of newly generated building MS in 2020. The embodied carbon in each life cycle stage is valuable for further lifecycle-based policy designs for: (i) supporting the updating of the green building certification system with consideration of the embodied carbon; (ii) promoting the green building material application and certification; and (iii) reducing the embodied carbon intensity from compact urban planning policy, such as the urban agglomeration policies in GBA. The goal of this paper was to shed a light on reducing carbon emissions from the perspective of the entire lifecycle and promote the development of net zero carbon buildings in China and Asia-Pacific.

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1. Introduction

Carbon emissions from buildings are imperative to understand the carbon neutrality strategy and the net zero society (Miatto et al., 2021; Mohammadizazi and Bilec, 2023). In typical de-industrialized mega cities including Tokyo, London, and Hong Kong, over 50% of carbon emissions originate from the building sector (Shen et al., 2021; Chen et al., 2023). Therefore, this sector needs to be considered for the transition to a de-carbonized society (Biswas, 2014; Zhang et al., 2019).

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Table 1

Initiatives and regulations updates for net zero carbon buildings, from a lifecycle perspective.

Aspects of net-zero carbon buildings	Policies & initiatives	Scope of emission	Examples
Green building management and certification	Developing certificating system to guide the application of green materials with low emissions and building energy efficiency approaches.	whole life-cycle embodied carbon emission	<ul style="list-style-type: none"> • LEED: United States • BREEAM: United Kingdom • CASBEE: Japan • Green Mark: Singapore • BEAMS Plus: Hong Kong SAR • High Quality Environmental standard: France • European Union, United States, Hong Kong SAR, Singapore
"Advancing Net Zero" is World Green Building Council's global project	Calls for stakeholders and authorities in business, organizations, cities, and countries and regions to realize net zero operating emissions by 2030 and for all buildings to be net zero in operation by 2050.	Operational emission	
Green construction materials	Establish recommended material inventory, which is low embodied emissions	whole life-cycle embodied carbon emission	<ul style="list-style-type: none"> • British Standards Institution label for Construction products (BSI) • The Green Roofs for Healthy Cities: North America • Nature Based solutions: European Union • Climate-related information disclosure guidance by Financial Stability Board and its Task Force on Climate-Related Financial Disclosures from 2017 and updated in 2021.
Procure high-quality carbon offsets	Applied nature-based solutions to increase carbon sequestration effects and offset embodied carbon emissions.	Sequestration of carbon emissions	
Reduce scope 3 emissions	Initiatives and information disclosure for construction companies to report their scope 3 emissions (in supply) and actions to mitigate climate risk.	Upstream emissions (product stage)	

Source: Adapted from our previous work: [Chen et al. \(2023\)](#).

the building and construction sector ([Hao et al., 2022](#); [Liu et al., 2022](#); [Tong et al., 2023](#)).

Against this background, the industries (e.g., the World Green Building Council) and academia have promoted a series of initiatives regarding Net Zero Carbon Buildings and Net Zero Society ([Dong et al., 2021](#); [Chen et al., 2023](#)). These initiatives have further led to updates and innovation on technologies and regulations in the building sector, such as the adaptation of entire-life building carbon emissions into the current green building certificates system, along with low carbon and low impacts construction materials development and certificates standards. Such strategies strongly support the low-carbon transition of the building sector from the perspective of the supply chain, and help to reduce the lifecycle carbon emissions of buildings, including both direct and embodied carbon ([Wang et al., 2018, 2019](#); [Shah et al., 2020](#)). [Table 1](#) summarizes the important updates with respect to carbon emissions from buildings. Therefore, estimating the embodied carbon of a building, based on the calculation of building stocks, would be valuable to support the above initiatives on building materials technologies, regulations, standards and scenarios simulation for science-based targets in the building sector. However, the studies that account for the building embodied carbon emissions on the urban scale are limited.

Existing literature is mainly based on three approaches to conducting the analysis of embodied carbon emissions of buildings:

- Examined the embodied carbon at a micro level (bottom-to-top approach) that was applied with a lifecycle assessment on single buildings. These studies mainly calculated the embodied carbon of buildings based on the material inventory of single buildings, with the help of a lifecycle inventory database and/or process inventory data. ([Van Ooteghem and Xu, 2012](#)) applied ATHENA EIE for Buildings v4.0.64 to find the whole lifecycle carbon emissions of five commercial buildings in Canada based on the building material inventory. [Biswas \(2014\)](#) calculated the life cycle carbon emissions of a single commercial building in Australia, along with assessing the carbon emission in material production, transportation, building construction and operation.

([Monahan and Powell, 2011](#); [Kang et al., 2015](#)) used the life-cycle inventory database to evaluate the whole life cycle carbon emissions of six buildings in Korea and one building in the United Kingdom, based on the direct investigation of single building material inventory. ([Zhang and Wang, 2016](#)) applied a similar approach to account for the whole life cycle carbon emissions of four buildings (including one residential building) in Harbin, China. This process-based approach can estimate the life-cycle carbon emissions of single buildings relatively accurately based on the detailed material inventory, and its scope can basically cover the entire life cycle of the building. However, such an approach is difficult to expand to a city or regional scale, considering the large number of buildings present in the area.

- Estimated the macro-level building-related lifecycle carbon emissions, based on the national or regional panel data of building materials inventory. These studies estimated the yearly materials inputs, stocks and outputs according to statistical data or MS estimation model. Based on the material inventory data in the statistics, these studies were able to calculate the carbon emissions in material production, transportation, building construction, operation and maintenance phase, as well as building waste treatment and recycling. [Zhu et al. \(2022\)](#) utilized statistical data in the construction industry to estimate the embodied carbon emissions (cradle to grave) in the building sector (China national scale) for a single year as well as in a time series to predict the future scenario (1950–2060). [Chen et al. \(2022\)](#) employed the statistics of building area data to estimate the building materials and stocks to calculate the embodied carbon emission with respect to building material production and transportation on the China national scale (cradle to gate). [Peng et al. \(2021\)](#) applied similar procedures and used the statistical data of building areas to estimate the embodied carbon of buildings (cradle to grave) in the Greater Bay Area, China. A few other studies applied macro-level building material flows and stocks models to estimate the dynamic building stocks as the foundation to account for the embodied carbon in buildings. [Zhong et al. \(2021\)](#) estimated the embodied

- carbon emissions for building materials production (cradle to gate) on a global scale that was based on a dynamic building material assessment model (BUMA). The Ecoinvent database was utilized to conduct the life cycle assessment on carbon emissions. [Arehart et al. \(2022\)](#) applied a similar approach based on the Open Dynamic Material Systems Model (ODYM) to estimate the embodied carbon emissions for building materials production (cradle to gate) in the United States by conducting a time series analysis from 2020 to 2100. To summarize, these macro-level studies were able to estimate the building embodied carbon of buildings at different life cycle stages using a top-down approach; however, they failed to capture the specific building's information. Hence, these studies could not realize the spatialization of building MS and the related embodied carbon.
- c. Applied a hybrid method, which combines the spatial approach for the estimation of building material stocks (MS) from bottom to top, along with the estimation of life cycle carbon emissions. The method was applied to examine the building material production-related carbon emissions and spatialization in Beijing, China ([Mao et al., 2020](#)), built-up districts in United Kingdom ([Ajayebi et al., 2021a, b](#)), and New York state in United States ([Heisel et al., 2022](#)). [Soonsawad et al. \(2022\)](#) expanded the estimation of embodied carbon from material production to transportation and building construction in Australia at the national level. This method was able to analyze the building's features (shape, location, etc.) and the embodied carbon; nevertheless, it was laborious to conduct detailed lifecycle stages analysis and time series analysis. This was because of the difficulty in distinguishing the lifecycle stage of the building within the spatial unit. As a result, most studies using this method estimated the cradle-to-gate emissions to conduct the spatialization for this stage.

Against this background, this study tried to examine the embodied carbon emissions of buildings in the Guangdong-Hong Kong-Macau Greater Bay Area (GBA) in China in 2020. The area contains 11 cities including international megacities such as Hong Kong, Shenzhen, and Guangzhou. We applied the hybrid approach with remote sensing techniques, for instance, night-time light data (NTL), building materials' intensity data, and a spatial analytical method for built-up area identification and building volume estimation, to calculate and spatialize the MS. Based on the spatial explicit MS data, we further applied lifecycle assessment to account for the embodied carbon in these buildings. Varying from the past studies that utilized the hybrid approach that mainly focused on the material production stage, we assessed the full lifecycle stages from "cradle to grave". The results are expected to support further applications in lifecycle-based policy design and simulation. This paper aims to shed light on reducing carbon emissions from the perspective of the entire lifecycle and promote the development of net zero carbon buildings in China and Asia-Pacific.

The remainder of the paper is organized as follows. Following the introductory section, [Section 2](#) introduces the methodology and materials. The results and discussions are presented in [Section 3](#), while [Section 4](#) shows the conclusions and life cycle-based policy recommendations.

2. Materials and methods

2.1. Overview

The estimation of MS is the foundation to calculate the embodied carbon in buildings. The methodology for the estimation of MS

is based on connecting the method of mapping the MS in the scale of urban built-up area cells (BACs), previously reported by ([Peled and Fishman, 2021](#)), and also modified in our previous study ([Liang et al., 2023](#)). Based on this, LCA is applied to the in-use building MS and their embodied carbon is calculated. A flow chart to conduct the estimation of MS and carbon emission is outlined in [Fig. 1](#). Our model consists of three main steps to estimate the MS and embodied carbon emission in the urban agglomerations:

- (i) Division of built-up areas: We employ a watershed detection method to partition the built-up areas based on the NTL data. This step enables us to distinguish local centers of human activity based on the luminous characteristics of night lights as built-up area units.

- (ii) Building volume estimation: Utilizing the observed building volume and NTL radiance values obtained from the sample cities, we developed models to estimate the volume of buildings within each built-up areas; These models, based on the built-up area as units, enable us to extrapolate and estimate the building volumes across the entire urban agglomerations.

- (iii) MS and carbon emission estimation: By combining the building volumes obtained in step (ii) with the material intensities (MI), we calculated the total MS in GBA in 2020. For these accumulated total MS, we separated out the newly generated MS in 2020 and used process-based LCA to calculate the embodied carbon emissions over their life cycle.

2.2. Total building material stocks (MS) estimation

Differing from previous studies that adopted a unified spatial grid ([Mao et al., 2020; Ajayebi et al., 2021a](#)), this paper delimits the shape units of the built area independently after processing the NTL data. As shown in [Fig. 2](#), the watershed-based delineation generates individual built-up area unit in cities for MS accounting and mapping. We named the resulting units as built-up area cells of NTL (BAC). This kind of method was first used to estimate the stock of building materials in Europe ([Peled and Fishman, 2021](#)).

Using this approach from the NTL data, we can classify each built-up area as a completely separate spatial unit without consulting external sources of information, such as political boundaries. The separate spatial unit also appears more in line with the actual boundary of built-up areas. Secondly, we further divide BAC clusters according to the luminescence efficiency inside the built-up area units. For each cluster, by analyzing the internal relationship between building volume and night lighting within BACs, mathematical models are developed to estimate the building volume in built-up area units. Furthermore, according to the varying building structures, the material intensity (MI) is used to calculate the MS of built-up area unit in GBA. The accounting formula of MS can be expressed as Eq. (1):

$$MS_{j,k,l} = \frac{VOL_j}{FH} \times \theta_k \times MI_{k,l} \quad (1)$$

Where $MS_{j,k,l}$ donates the MS in the j^{th} BAC, k donates the structure of building, and l donates the type of building material; VOL_j donates the building volume in the j^{th} BAC; FH is the average floor height; θ_k is the proportion of building volume of two different building types in total building volume within j^{th} BAC; and $MI_{k,l}$ represents the material intensity of the l^{th} material in the k^{th} building type (k , kg/m²).

Referring to the research of [Hu et al. \(2010\)](#), we determined the structure of buildings according to their building floors, (i) brick-concrete structures (BC)—the building has less than 7 floors, and (ii) reinforced concrete structures (RC)—the building has more than 7 floors; MI of different building structures comes from the previous research of urban MS accounting in China ([Shi et al., 2012; Guo](#)

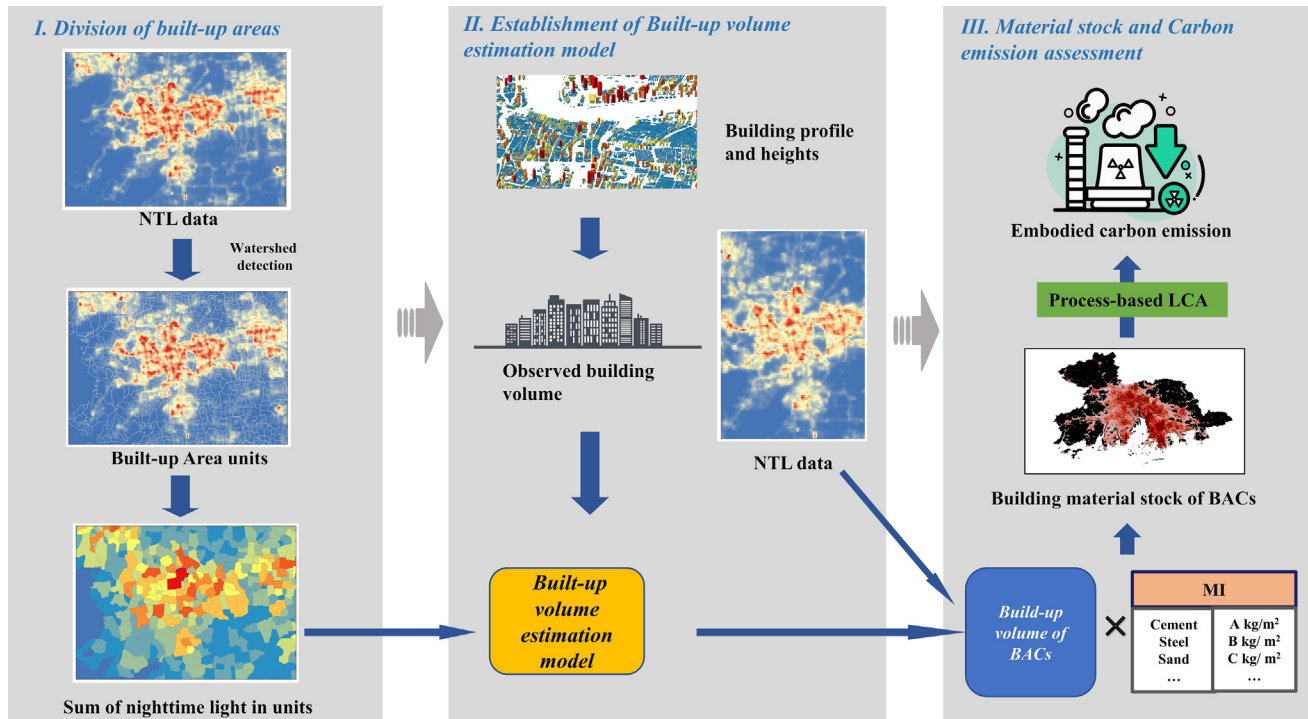


Fig. 1. Building material stocks and embodied carbon estimation approach Source: the division of built-up area is enlightened by (Peled and Fishman, 2021), and the whole procedure is based on our previous work (Liang et al., 2023).

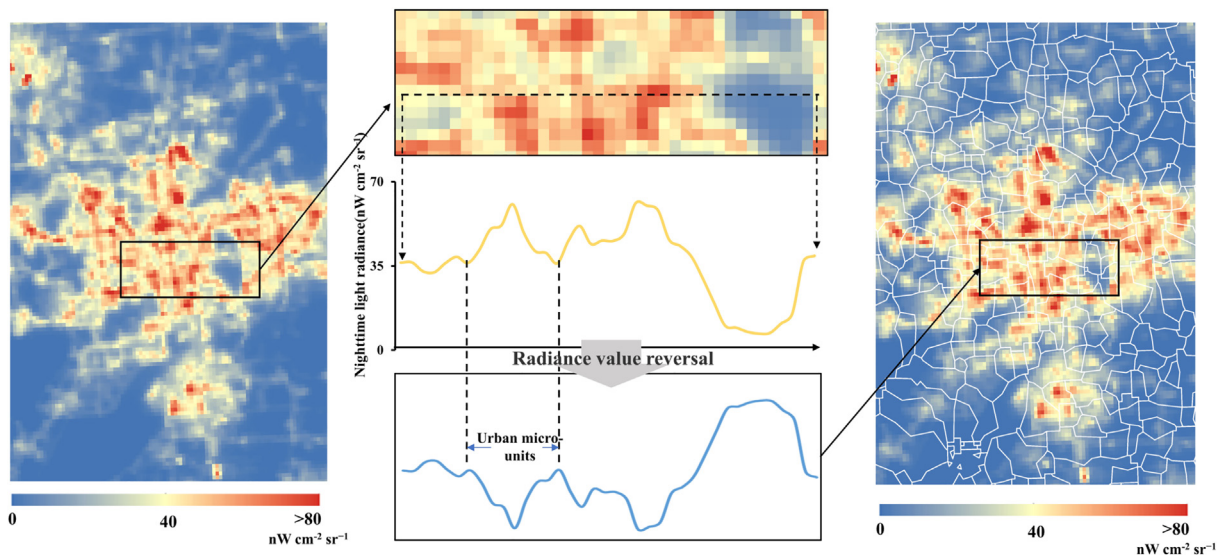


Fig. 2. Illustrative schematic of the delineation of Built-up Area Cells of NTL (BACs). Source: adapted from Peled and Fishman (2021) and improved in our previous study (Liang et al., 2023).

et al., 2019), which were used to obtain the calibration MI of two building structures in this study (Table 2).

2.3. Accounting for the embodied carbon in newly generated MS

The embodied carbon emission accounting scope of this study is the whole life cycle of newly generated MS in GBA in 2020. Based on the different process of building materials from mineral extraction (P1) to waste disposal (E1), we further integrate the life cycle of the building into five stages: building materials product stage, construction stage, use stage, demolition stage and end-of-life

stage. Fig. 3 illustrates the detailed scope of embodied carbon in buildings based on lifecycles. In order to clearly distinguish the life cycle stages of the building, we have separated the newly generated MS in 2020 from the total MS. For new buildings built in 2020, we assume they were at the same life cycle starting point to eliminate the effects of different building ages. According to the data recorded in the China Statistical Yearbook, the proportion of newly completed construction area to the total building floor area in 2020 were calculated. By combining this proportion with the total MS, we calculated the newly generated MS of buildings. The specific calculation process is as Eq. (2)–(4):

Table 2
Calibrated average material intensity (kg/m²).

Building type	Steel	Cement	Sand	Gravel	Brick	Wood	Total
Brick-concrete	24.5	193.5	719.0	561.5	623.0	29.0	2150.5
Reinforced-concrete	77.5	328.0	619.0	815.5	125.0	26.5	1991.5

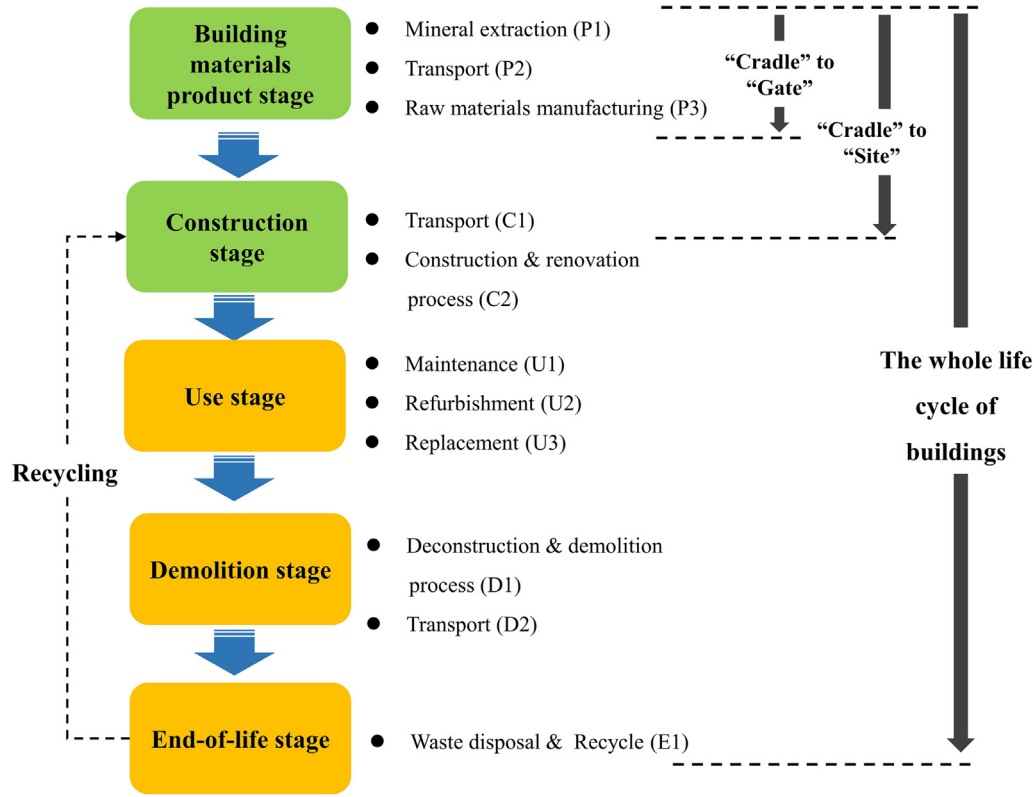


Fig. 3. Lifecycles of construction activities and building management.

$$MS_{new} = \eta\% \times MS_{tot} \quad (2)$$

$$\eta\% = \frac{area_{new}}{area_{tot}} \quad (3)$$

$$area_{tot} = Cap_{floor} \times Pop \quad (4)$$

Where MS_{new} represents the newly generated MS of buildings in 2020; $\eta\%$ represents the proportion of newly generated MS in the total MS in 2020; MS_{tot} represents the total MS of buildings in 2020; $area_{new}$ is the completed construction area in 2020; $area_{total}$ is the total building floor area in 2020; Cap_{floor} is the per capita floor area; and Pop is the population.

In calculation, embodied carbon in the building material product stage includes the embodied carbon from “Mineral extraction” (P1), “Transport” (P2), and “Raw materials manufacturing” (P3). The embodied carbon in the construction stage aims to “Transport” (C1) and lead the “Construction & renovation process” (C2). Furthermore, the embodied carbon in the use stage considers “Maintenance” (U1), “Refurbishment” (U2) and “Replacement” (U3), while embodied carbon in the demolition and end-of-life stages aims to conduct “Deconstruction & demolition process” (D1), “Transport” (D2), “Waste disposal & Recycle” (E1).

As shown above, the annual embodied carbon emissions (C_{emb}) in the building sector can be calculated as Eq. (5):

$$C_{emb} = C_{pro} + C_{con} + C_{use} + C_{deo} + C_{end} \quad (5)$$

Where:

C_{emb} is the total carbon emitted in the whole life cycle of buildings.

C_{pro} is the total carbon emitted in the building materials product stage.

C_{con} is the total carbon emitted in the construction stage.

C_{use} is the total carbon emitted in the use stage.

C_{deo} is the total carbon emitted in the demolition stage.

C_{end} is the total carbon emitted in the end-of-life stage.

(i) *The carbon embodied in the building materials product stage*

The manufacturing process of building materials generates the largest proportion of embodied carbon during the life cycle of a building. First, the stock of building materials is calculated. This study only calculates the embodied carbon from newly generated MS in 2020. Material-based emission factors were obtained from literature and standards (Table 3), which covers all the processes of building materials from mineral extraction to material manufacturing (cradle to gate). The calculation process of the carbon embodied in the building materials product stage can be presented as Eq. (6):

$$C_{pro} = C_{ext} + C_t + C_{man} = \sum_{i=1}^J (MS_i \times EF_i) \quad (6)$$

where, C_{pro} is the total carbon emitted in the building materials production stage; C_{ext} , C_t and C_{man} represent the embodied carbon from “Mineral extraction”, “Transport”, and “Raw materials manufacturing”, respectively; I denotes the type of building material, which

Table 3
Carbon emission factors of building materials in China.

Material type	Carbon emission factor (kg CO ₂ / t)	Transportation carbon emission factor (kg CO ₂ / t*km)	Distance (production site to the construction site) (km)
Steel	2380	0.057	500
Wood	200	0.179	500
Cement	735	0.057	40
Brick	292	0.179	500
Sand	2.51	0.057	40
Gravel	2.18	0.057	40

further determines the material-based carbon coefficient; MS_i is the stock of the i^{th} building material; and EF_i is the material-based emission factor.

(ii) *The carbon embodied in the construction stage*

Carbon emissions in the construction stage mainly include carbon emissions from the transportation of building materials (C_t) and the construction process (C_{oc}), as Eq. (7):

$$C_{con} = C_t + C_{oc} \quad (7)$$

where C_t is the total carbon emitted during the transportation of building materials from factories to site; C_{oc} is the carbon emissions from the on-site construction process;

Embodied Carbon emissions from the transportation of building materials can be estimated based on transportation mode, distance and vehicle load, and the energy consumption of transportation. The vehicles for building material transportation are either medium diesel trucks or heavy diesel trucks. Table 3 summarizes the transportation carbon emission factors of building materials and the average distance from the production site to the construction site. The carbon emission content in the transportation process of building materials is shown in Eq. (8):

$$C_t = \sum_{i=1}^j (MS_i \times D_i \times TEF_i) \quad (8)$$

where MS_i is the stock of the i^{th} building material; D_i is the mean transportation distance of the i^{th} building material; and TEF_i is the transportation carbon emission factor of the i^{th} building material.

The carbon emissions from the construction of buildings are mainly caused by the energy consumed by on-site machinery and equipment (e.g., loaders and cranes, etc.). The construction energy consumption and energy carbon emissions factors during building construction and demolition can be accessed from statistics available in China Construction Industry Yearbook and Building Carbon Emission Calculation Standard, which are applied in this study (Table 4). There are eight main sources of energy used during the construction process. The carbon emissions content in the construction process can be calculated as Eq. (9):

$$C_{oc} = \sum_{n=1}^m (E_n \times EF_n) \quad (9)$$

where C_{oc} is the total carbon emitted during on-site construction; n denotes the type of energy; E_n is the consumption of the n^{th} type of

Table 4
Energy consumption and emission factors for building construction and demolition in 2020 in GBA.

Energy	Unit	Energy consumption	Emission factor (ton/ton, kWh, or m ³)
Raw Coal	10 ⁴ tons	3.87	1.98
Gasoline	10 ⁴ tons	45.13	2.99
Kerosene	10 ⁴ tons	0.27	3.1
Diesel Oil	10 ⁴ tons	17.96	3.16
Fuel Oil	10 ⁴ tons	0.56	3.24
Electricity	kWh	50.12	0.792

energy; and EF_n is the carbon emissions factor of the n^{th} type of energy.

(iii) *The carbon embodied in the use stage*

Carbon emissions in this stage mainly come from processes related to building maintenance, refurbishment, and replacement. In addition to the main structure, the building also contains components such as tiles, doors and windows, decorative panels, etc. Their service life is often shorter than the building itself; hence, these components need to be replaced and refurbished during the building's use stage. The calculation of emissions from building material production and construction stage can be used to assess the carbon emission of materials required for renovation during the manufacturing, transportation, and construction phases. In previous studies, it has been determined that the annual newly embodied carbon in the building use stage is between 0.3% and 2.8% of the initial embodied carbon of the building, which is the carbon embodied in the building material product stage and the construction stage (Dixit, 2019). Considering that the average life span of a building in China is between 30 and 50 years, and the frequency of component replacement increases with the age of the building, we further determine the recurring embodied carbon emissions in the use stage accounting for about one-third of the initial embodied emissions (Wang et al., 2016). The carbon emissions in this stage can be calculated as Eq. (10):

$$C_{use} = \sum_{i=1}^j \alpha_i (\%) \times [C_{pro(i)} + C_{con(i)}] \quad (10)$$

where C_{use} is the total embodied carbon emissions in the use stage; C_{pro} is the total production embodied carbon emissions; and C_{con} is the total embodied carbon emissions of the building construction process. α_i is the proportion of the embodied carbon emission of the i^{th} material in the use stage to the initial embodied carbon emission.

(iv) *The carbon embodied in the demolition stage*

The carbon emissions in this stage mainly include the carbon emissions of building deconstruction and demolition, as well as construction waste transportation. These carbon emissions are calculated in a manner similar to the construction stage. Furthermore, the amount of construction waste produced can be obtained from the demolition rate of the building. Recyclable materials from construction waste, such as steel, sand, and gravel, are shipped to recycling stations for reprocessing, while other construction waste deemed unrecyclable goes to landfills.

Based on previous research, we assumed that the average distance of transporting recycled construction materials to the recycling site is 50 km, and the average distance of transporting waste construction materials to the landfill site is 30 km (Table 5). The calculation process of the carbon embodied in the demolition stage can be presented as Eq. (11)–(13):

$$C_{deo} = C_{od} + C_t \quad (11)$$

$$C_{od} = \sum_{n=1}^m (E_n \times EF_n) \quad (12)$$

$$C_t = \sum_{i=1}^j (QW_i \times D_w \times TEF_i + QR_i \times D_r \times TEF_i) \quad (13)$$

where C_{deo} is the total embodied carbon emissions of the building demolition process; C_{od} denotes the embodied carbon during on-site demolition; C_t is the transportation carbon emissions of the building demolition waste; n denotes the type of energy; E_n is the consumption of the n^{th} type of energy; EF_n is the carbon emissions factor of the n^{th} type of energy; QW_i is the quantity of non-recyclable demolition waste of the i^{th} building material; D_w is the mean transportation distance (demolition site to landfill site) of the non-recyclable demolition waste; QR_i is the quantity of recyclable demolition waste of the i^{th} building material; and D_r is the

Table 5

Transportation distances for demolition wastes and wastes recycling.

	Demolition site to landfill site (D_W)	Reported value	Demolition site to recycle site (D_r)	Reported value
Distance	30 km	30 km (Peng, 2016)	50 km	35 km–60 km (Luo et al., 2022; Wu et al., 2012)

mean transportation distance (demolition site to recycle site) of the recyclable demolition waste. For the unit value of transportation-related emission, we can apply a similar approach as Eq. (8); TEF_i is the transportation carbon emission factor of the i^{th} building material or waste. Table 5 summarizes the related values of distance.

(v) *The carbon embodied in the end-of-life stage*

The embodied carbon emissions of this stage mainly emerge from the recovery and reuse of construction waste. It is assumed that the recovery rates of steel, sand, and gravel in the final disposal are 50%, 30%, and 30%, respectively (Table 5). For landfill waste, only the carbon emissions resulting from transportation in the previous stage are to be counted. The carbon emissions can be calculated as Eqs. (14) and (15):

$$C_{end} = \sum_{i=1}^j (QR_i \times REF_i) \quad (14)$$

$$QR_i = A\% \times MS_i \times R_i \quad (15)$$

where C_{end} is the total embodied carbon emissions in the end-of-life stage; QR_i is the quantity of reused i^{th} building material; REF_i is the recycled carbon emission factor of the i^{th} building material, which could be obtained from literature and standards (Table 5); $A\%$ is the demolition waste generation rate of buildings, it is applied as 80% in this study, and the justification is provided in **Supplementary Data Table S3**; R_i is the recyclable rate for the i^{th} building material (Table 6).

2.4. Data source and preprocessing

2.4.1. Building profile and heights

In this study, the observed building volumes were determined from building profile and height data. The GIS data of building profile and height used in this study was obtained from the Autonavi map, including the shape, location, and height information. We employed the data for the year 2020 from five cities (i.e., Guangzhou, Shenzhen, Foshan, Dongguan and Zhongshan) for estimation and validation purposes. The data from Guangzhou, Shenzhen and Foshan were used for model development, whereas the data from Dongguan and Zhongshan were used for model validation. The calibration and verification is provided in **Supplementary Data Fig. S1**.

Table 6

Carbon coefficients and recycle rates for selected materials.

Material type	Recycled carbon emission factor (kg CO ₂ /t)	Reference and note	Recycle rate of materials	Reference and note
Steel	1190	The embodied energy of recycled steel is 20%–50% of the embodied energy of virgin steel (Gao et al., 2001; Chen et al., 2022)	50%	Zhang and Wang (2016, 2017).
Sand	2.59	Since energy is required to crush the waste concrete, the energy use of recycled gravel and sand is 5% higher than virgin materials (Gao et al., 2001; Chen et al., 2022).	30%	Gravel and sand can be substituted by crushed waste concrete, and concrete with up to 30% of aggregate replaced by recycled aggregate is acceptable (Tam and Tam, 2006; Chen et al., 2022)
Gravel	2.29		30%	

Note: This study only considers the reuse and recycling of steel, sand and gravel based on the real condition of the case area.

2.4.2. Nighttime lights

“The Defense Meteorological Satellite Program Operational Linescan System” (DMSP-OLS) and “Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite” (NPP-VIIRS) are two NTL datasets that have been widely used by existing studies. However, there are differences in spatial resolution and sensor design between the two sets of data; therefore, correction and fusion of the two data sets are required to obtain continuous annual NTL data.

In this study, we used the extended time series (2000–2020) NTL data, which is accessible at: <https://doi.org/10.7910/DVN/YGIVCD> (Chen et al., 2021). In the dataset, DMSP-OLS and NPP-VIIRS are used to acquire basic nighttime light data before the auto-encoder is applied to combine them. In view of its continuous long-term series, this database has great potential to be used in the study of MS evolution.

2.4.3. Material intensity

MI is one of the most common used and important indicators in buildings metabolism analysis (Yang et al., 2020). Accurately estimating MI is crucial for an accurate assessment of material inventory. The variation in building structures, functional types, and construction years across Chinese provinces makes it extremely challenging to obtain regional detail information on MIs. Unlike countries such as Japan, the United Kingdom, and Sweden, where a comprehensive MI database system has already been established, China has not documented MIs adequately (Guo et al., 2019). Over the years, researchers have been calculating specific MIs on the Chinese national scale. And in this study, we adopted the calibrated average MI in China calculated by Guo et al. (2019). Firstly, buildings were classified into masonry and reinforced concrete based on the number of floors. Secondly, considering the proportion of residential/non-residential buildings and building categories, the latest cohort of MI coefficients from Shi et al. (2012) were averaged to obtain the calibrated MI for masonry and reinforced concrete buildings in this study.

2.4.4. Emission factors

The emission factors (EF) are important for the calculation of embodied carbon. We mainly used the emission factors from literatures and standards (Standard for Building Carbon Emission Calculation in China). The material-based emission factors, transportation related emission factors, as well as construction

related emission factors are summarized and justified in [Supplementary Data Tables S2 and S3](#).

2.4.5. Demolition waste generation rate

The demolition waste generation rate of building materials is important to determine the generation amount of building wastes, the potential recycled materials amount and the embodied carbon. The value and justification is provided in [Supplementary Data Table S3](#).

3. Results and discussions

3.1. Study area

Case study is conducted in the Guangdong-Hong Kong-Macao Greater Bay Area (GBA), which is one of China's urban agglomerations with the fastest social and economic development, the largest population density and the highest level of urbanization ([Fig. 4](#)). GBA consists of nine cities in Guangdong Province (Guangzhou, Shenzhen, Zhuhai, Dongguan, Foshan, Zhongshan, Huizhou, Jiangmen, and Zhaoqing), and two SARs (Hong Kong and Macao). In 2020, the built-up area of GBA reached 4,828.38 km², with an urbanization rate of 86.10% ([NSBC, 2020](#)). The GBA is expected to build a new open economic system and further integrate into the world economy ([Bi et al., 2020](#)).

In 2019, the total planned investment in major construction projects in GBA exceeded 4.5 trillion yuan (Guangdong Development and Reform Commission ([GDDRC, 2020](#))). The rapid increase of urban building construction leads to the continuous increase of MS and energy consumption, thereby causing severe secondary pollution. This poses challenges to sustainable urban development within the GBA.

3.2. MS estimation results

This section describes MS estimation results for 2020 in detail. [Fig. 5](#) shows the spatial distribution of MS at the cellular scale,

while [Fig. 6](#) is a comparison of GBA city-scale MS accounting results.

[Fig. 6](#) further displays BACs and their MS densities (tons/km²) in GBA. The average MS density of BACs in GBA is 379,336.58 ton/km², with the minimum value being 4,207.97ton/km² (found in Zhaoqing), and the maximum value being 8,536,706.48 ton/km² (found in Hong Kong). The spatial distribution of MS in GBA exhibits significant regional variations. Perhaps influenced by the special economic zone policy, MS in GBA has concentrated in the "Guangzhou-Hong Kong line" area. In the process of extending to the edge of urban agglomeration, the influence of special zones has gradually declined. In GBA peripheral cities (such as Zhaoqing, etc.), there is almost no BAC with MS density exceeding 10Mt/km².

The total amount of MS within GBA in 2020 was 13,851.70 Mt (cf. [Fig. 6A](#)), among which Guangzhou (2,943.68 Mt), Shenzhen (2,859.23 Mt) and Dongguan (2,811.60 Mt) are the three cities with the largest MS. Unsurprisingly, bulk materials such as cement, gravel, sand, and brick, which are mainly used in construction, constitute the majority of the total material inventory. When combined, they made up 96.4% of the total MS, similar to the range (93%–97%) estimated by [Chen et al. \(2016\)](#). Although steel accounts for a relatively small proportion of the total stock at about 2.2%, it depicts the highest recycling rate among building materials and is one of the most recyclable building materials ([Gordon et al., 2006](#)). Among GBA cities, Shenzhen has the highest steel recycling potential, with its steel stock reaching 67.01 Mt.

As shown in [Fig. 6C](#), the MS density of each city in GBA varies between 0.11 Mt/km² and 3.02 Mt/km². The mean and standard deviation of MS density were 0.832 Mt/km² and 0.34 Mt/km², respectively. Amongst the cities observed, Macao's MS density is far higher than other cities, reaching 3.02 Mt/km². In Macao, due to the limited administrative area, there is almost no idle land for urban expansion. Therefore, the material inventory brought by rapid urbanization can only be accumulated in the vertical direction, resulting in an increasing MS density. Among other cities, the MS density of Hong Kong, Shenzhen and Dongguan exceeded 1 Mt/km², matching the level of urban development. In

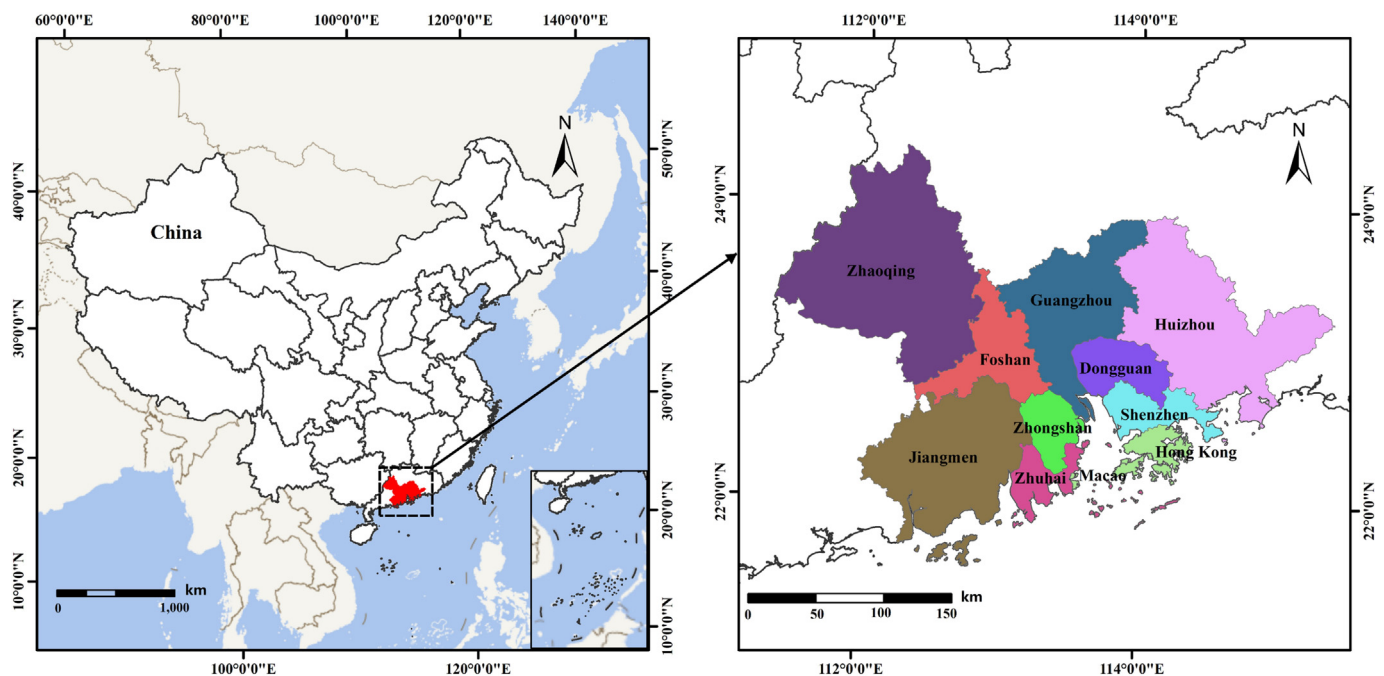


Fig. 4. Locations of the study area.

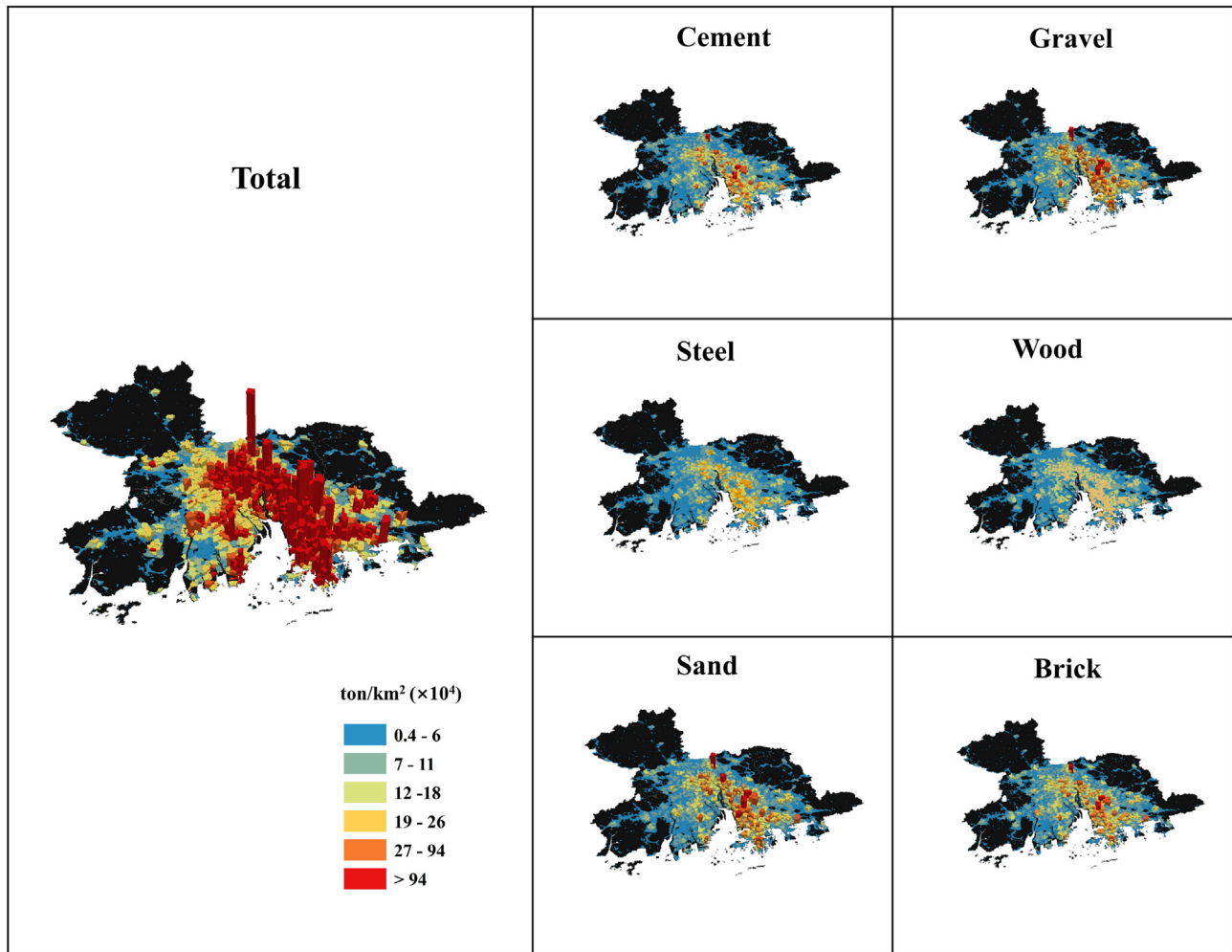


Fig. 5. Estimation results of building MS of GBA in 2020.

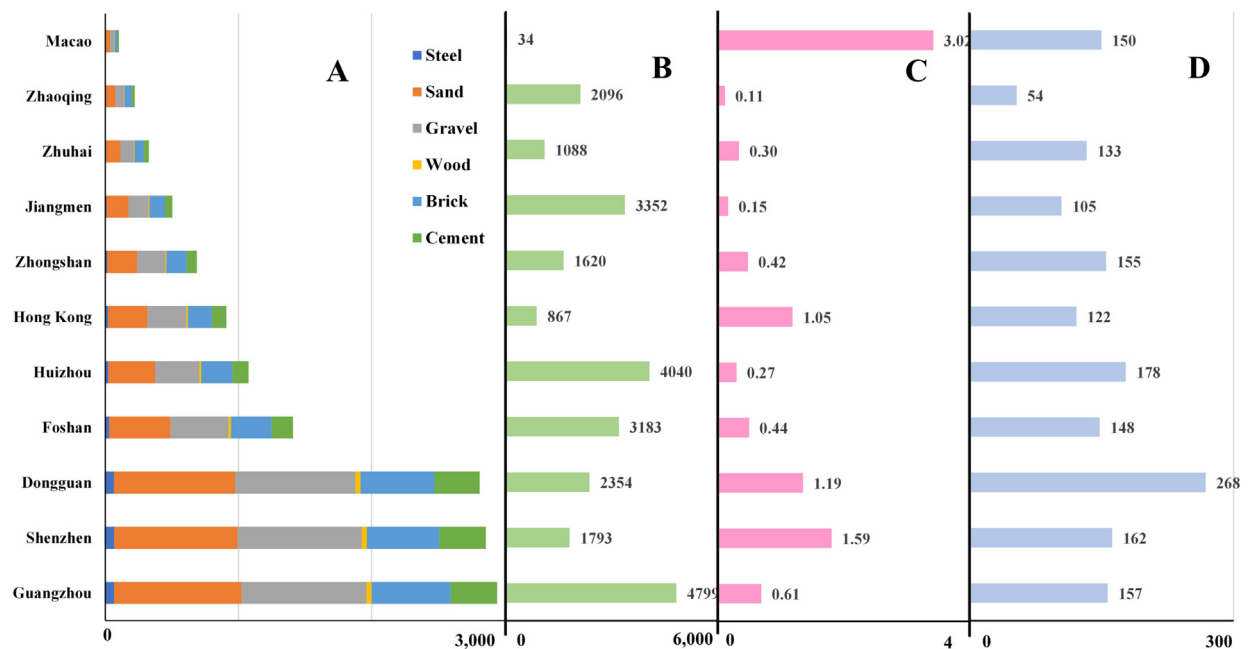


Fig. 6. (A) Total MS (Mt); (B) study area (km²); (C) MS density (Mt/km²); (D) MS per capita (t/cap). Note: The study area is the total coverage area of BAC in each city.

particular, Guangzhou has the highest MS but only ranks fifth in MS density, which may be related to its vast urban area. Fig. 6D shows the per capita MS of cities in GBA. These figures are slightly lower than the MS per capita in Japan (323 t/cap) as calculated by Tanikawa et al. (2015), suggesting that the GBA must continue to adjust demographics and building quality to achieve sustainable development.

3.3. Embodied carbon emission in buildings

During the life cycle of the building, a series of maintenance and renovation occurs. In addition, the demolition rate increases with the age of the building. For buildings of different ages, it is challenging to calculate carbon emissions during the use stage by employing uniform standards. Therefore, in the given space unit, the determination of the age of the building is the key point of carbon accounting in the use and demolition stages of the building lifecycle. In this study, in order to eliminate the differences in the carbon emissions at different lifecycle stages of buildings, we only conducted the embodied carbon accounting for the entire lifecycle of the newly generated building MS in 2020. Based on the completed area of the building from the Building Statistical Yearbook of China, we determine the ratio of the floor area of newly generated buildings to the total building floor area in 2020 (as detailed in section 2.3). Using this ratio, we estimate the newly generated MS in each GBA city in 2020 (Table 7).

Newly built buildings in GBA in 2020 are expected to produce a total of 163.12 Mt of carbon emissions during their lifecycles. Similar to the estimation results of MS, Guangzhou, Shenzhen and Dongguan are the three cities with the highest embodied carbon emissions from buildings (Fig. 7). The newly built buildings in these three cities in 2020 are expected to produce 33.97 Mt (Guangzhou), 33.32 Mt (Shenzhen) and 32.54 Mt (Dongguan) of embodied carbon emissions, respectively. Steel, brick, and cement represent 20%, 24%, and 27%, respectively, of the total embodied carbon in the newly generated buildings in 2020. These three building materials constitute more than two-thirds of the total embodied carbon, whereas sand, gravel, and wood only accounted for 3% of the embodied carbon. Moreover, other materials, including glass, tile, aluminum, linoleum, plastic, etc., together constituted 26% of the total embodied carbon. Notably, steel contributes 20% of the total embodied carbon, even though it was one of the least consumed building materials that only accounted for 2.2% of the total newly generated MS. In contrast, sand and gravel, while among the top two in the composition of MS, account for small proportions (2%) of carbon emissions generation.

From the perspective of the lifecycle stages (Fig. 8), the building materials product stage forms the largest proportion of embodied carbon during the lifecycle of buildings, generating a total of 100.74 Mt of embodied carbon emissions, accounting for 62% of

the total. The thermal energy required to manufacture building materials such as steel and cement is largely generated by burning large amounts of fossil fuels, which can emit large amounts of carbon. Embodied carbon emissions from the building use stage came in second at 39.05 Mt, accounting for 24% of the total. It mainly includes the carbon emissions related to building maintenance, refurbishment, and replacement during the use stage of the buildings. In contrast, the embodied carbon emissions of buildings during the construction, demolition and end-of-life stages are relatively low, accounting for only 14% of the total embodied carbon emissions.

3.4. Advantages and limitations

Previous studies on inventory primarily relied on government-published statistical data to establish MS models using static accounting methods. However, these methods differ significantly from remote sensing-based accounting methods. Static accounting methods heavily rely on non-local statistical data from other research or relevant departments, making it challenging to replicate and transfer the models to different regions and to analyze the spatiotemporal evolution of MS. In contrast, our approach utilizes globally and long-term available NTL data as the underlying dataset, enabling its application in other regions. NTL data, closely related to economic activity intensity, has been increasingly used to extrapolate MS (Liang et al., 2017; Yu et al., 2018). In this study, we divided NTL data by watershed to generate built-up area units, allowing for broader estimation of MS, including rural and suburban areas where statistical data are scarce. In our previous work (Liang et al., 2023), we successfully estimated the MS of buildings in the three major urban agglomerations along the eastern coast of China using a NTL based estimation model at the BAC scale, and analyzed their spatiotemporal evolution characteristics.

However, there are certain limitations to our study. Firstly, the NTL data we used cannot distinguish mixed light sources. Besides buildings, infrastructure such as roads can also contribute to light emissions, leading to an overestimation of the building MS. Future research could consider utilizing satellite imagery, such as LuoJia 1-01, which can identify different light sources (Zhao et al., 2023). Secondly, research indicates that specific building clusters, such as commercial centers, ports, mining areas, and horticultural buildings, may have higher nighttime light outputs, potentially resulting in an overestimation of MS in these areas (Peled and Fishman, 2021). Thirdly, accurate estimates of material inventory and embodied carbon emissions rely heavily on appropriate MI and EF. In this study, we referred to relevant literature and standards that provide calculated and reported MI and EF values applicable nationwide. However, the specific numerical values of these parameters may still vary slightly due to differences in building structures, construction styles, energy composition types, and

Table 7
Newly generated MS in GBA in 2020.

Cities	Cement	Steel	Sand	Gravel	Wood	Brick	Total
Guangzhou	2.34	34.37	33.71	1.42	21.27	12.59	105.68
Shenzhen	2.41	33.26	33.47	1.38	19.54	12.59	102.65
Dongguan	2.27	32.79	32.41	1.35	19.98	12.13	100.94
Foshan	1.03	16.54	15.64	0.68	10.94	5.78	50.61
Huizhou	0.78	12.63	11.92	0.52	8.41	4.40	38.65
Hong Kong	0.74	10.60	10.51	0.44	6.42	3.94	32.64
Zhongshan	0.49	8.08	7.57	0.33	5.44	2.79	24.71
Jiangmen	0.33	5.93	5.41	0.24	4.17	1.97	18.06
Zhuhai	0.24	3.83	3.62	0.16	2.54	1.34	11.73
Zhaoqing	0.14	2.61	2.35	0.11	1.88	0.85	7.95
Macao	0.09	1.19	1.22	0.05	0.67	0.46	3.68

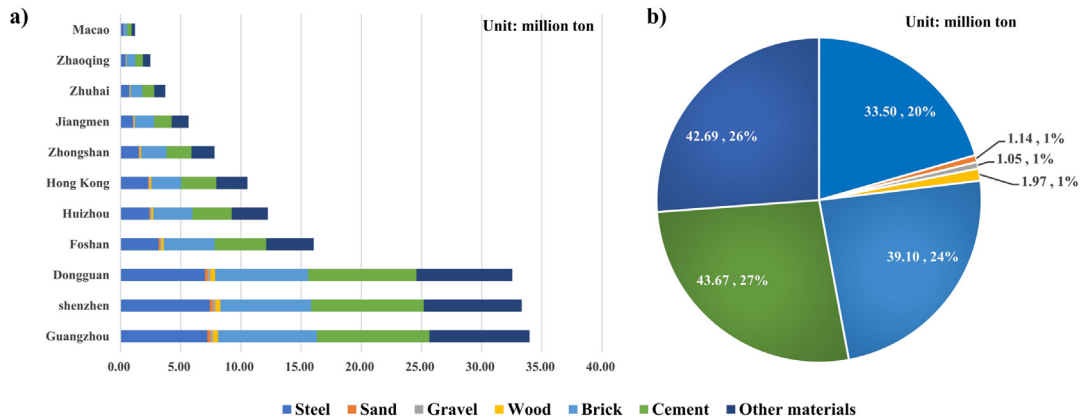


Fig. 7. Shares of the embodied carbon emissions of different building materials.

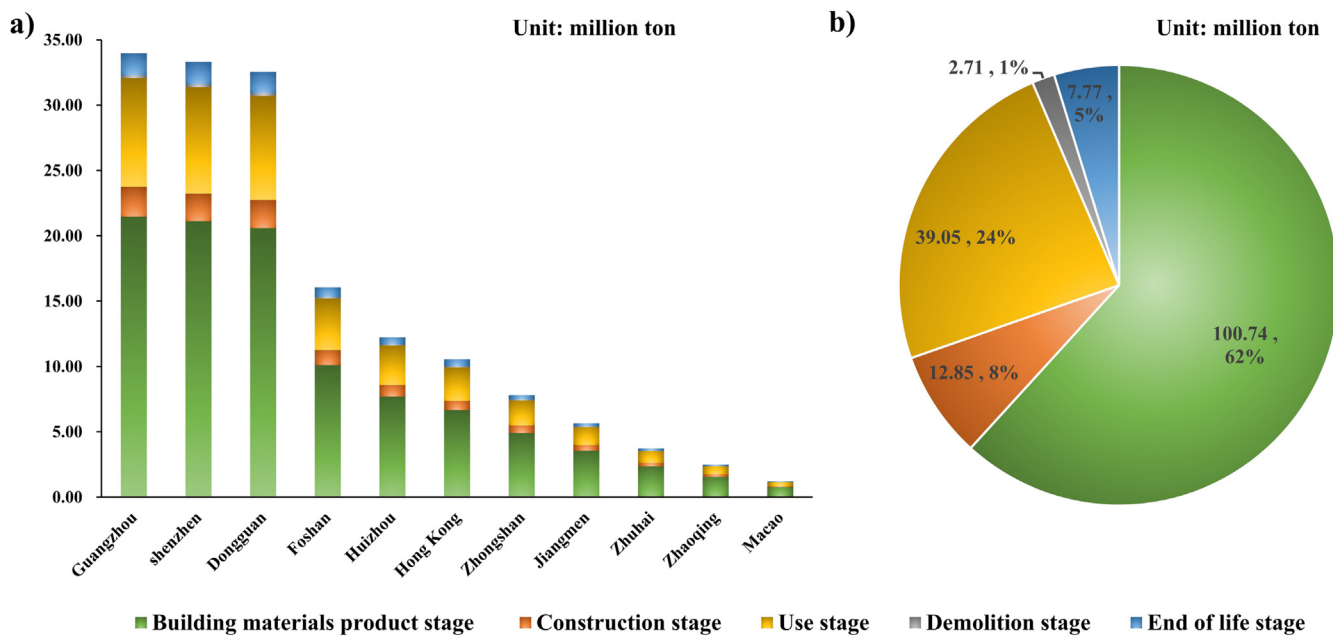


Fig. 8. Shares of the embodied carbon emissions of different life cycle stages.

other factors across different regions, which can impact the calculation results to some extent.

Regarding the estimation of embodied carbon, this study only considers the newly generated MS in 2020, including six building material (e.g., steel, sand, gravel, wood, bricks, and cement). There is still ample room for improvement in terms of the accounting scope. Additionally, certain processes in the life cycle of building materials were not considered due to data limitations. For example, construction waste undergoes landfilling or recycling may require sorting and crushing, which consuming energy and generating carbon emissions. The embodied carbon emission from these processes is relatively small relative to the total embodied carbon emission in the whole life cycle of the building, but in the future, we hope to explore these aspects further through field investigations (Zhu et al., 2020).

3.5. Prospects and outlook

This study calculates MS in the Greater Bay Area in 2020 and reveals the spatial distribution characteristics of MS. It can be found that the MS in the central cities of the GBA is large and closely connected, while the MS in the fringe area of the Greater Bay

Area urban agglomeration is small in scale and scattered in distribution, forming an obvious core-fringe pattern. To promote balanced development in the GBA, spatial guidelines can be derived from these spatial distribution characteristics. This includes focusing on infrastructure development and formulating policies for industrial transfer and upgrading. By strengthening connectivity between the core cities and surrounding areas, the integrated development pattern of the urban clusters can be reinforced. Further analysis should delve into the reasons behind the insufficient driving force of core cities towards the surrounding areas. Factors such as inadequate transportation networks and differences in industrial structure need to be thoroughly investigated. Additionally, strategies should be explored to address the issue of smaller MS in the peripheral areas, such as attracting investments and fostering emerging industries to stimulate economic development. It is also crucial to prioritize coordinated development within the urban clusters by enhancing cooperation mechanisms and resource sharing. This will contribute to achieving balanced development and sustainable prosperity across the entire Greater Bay Area region.

In addition, based on the quantitative information regarding the building-embodied carbon in the entire lifecycle, we can apply the

Table 8

Policy analysis on each life cycle stage of green construction & building and their contributions to circular economy.

Life cycle phases	Embodied carbon	Policy highlights under key CE elements
Raw materials manufacturing	<ul style="list-style-type: none"> 100.74 Mt in GBA. <p>The material embodied carbon is significant in the total embodied carbon emission in building stocks.</p>	<ul style="list-style-type: none"> Prioritize renewable resources, e.g., promotion of biomass based renewable construction material and green construction materials, which, with lower or even negative carbon emissions. Extend life-time of products: extend the life time of buildings. Reuse & Recycle: promoting demolition wastes recycle and recycle, to reduce the raw materials consumption. Design for the future creative building design to use more renewable materials. Application of digital technology: integrating block chain and carbon footprint to monitor, report and verify the carbon emission in the supply chain.
Transport	The embodied carbon emission mainly comes from the fossil fuels consumption in transportation.	<ul style="list-style-type: none"> Prioritize renewable resources: application of hydrogen and bio diesel. Reuse & Recycle: waste to energy for reducing fossil fuels consumption in transportation.
Construction & renovation process	12.85 Mt in GBA. The embodied emission mainly come from the material & energy consumption in construction & renovation activities.	<ul style="list-style-type: none"> Prioritize renewable resources: using more renewable materials and renewable energy. Design for the future: develop and promote prefabricated buildings.
Operational emission	Carbon emissions mainly come from the energy (electricity) consumed during building use. Particularly, in GBA, energy consumption is still dominated by coal.	<ul style="list-style-type: none"> Promotion of renewable energy and materials. Reuse, Recycle, and Circularity of the building parts.
Maintenance Refurbishment Replacement	<ul style="list-style-type: none"> 39.05 Mt in GBA. <p>Building renovation and interior decoration will consume corresponding building materials. The phenomenon of large-scale demolition and large-scale construction exists in many areas, and many buildings are forced to be demolished before reaching the life cycle, resulting in a waste of resources.</p>	<ul style="list-style-type: none"> Promotion of renewable energy and materials in green interior decoration Reduce & Reuse: Ensure that short-lived components can be repaired or replaced without damaging long-lived components. Promoting the green transformation of existing buildings, encouraging the renovation of old residential areas in cities and towns, and the renovation of dilapidated houses in rural areas. Retrofitting existing buildings rather than demolition and building new ones.
Deconstruction & demolition	<ul style="list-style-type: none"> 2.71 Mt in GBA. <p>The longer the life cycle of a building, the smaller the environmental impact per unit time. Compared with countries such as Europe and the United States, the average service life of buildings in China and GBA is generally shorter, only 20–30 years.</p>	<ul style="list-style-type: none"> Extend life-time of products: extend the building lifetime. Circular business model: develop novel circular business model between constructor, contractor and recycler. Team up to create joint value: boost value chain in the circular business. Application of digital technology: integrates carbon footprint approach and block chain to improve supply chain management.
Waste disposal & Recycle	<ul style="list-style-type: none"> 7.77 Mt in GBA. <p>The recycling and reuse of construction waste can effectively reduce the consumption of original building resources and carbon emissions in the production stage of building materials. However, there is still sufficient room for enhancing the recycling efficiency of building materials (such as currently there is only 50% of steel is full recycled in China).</p>	<ul style="list-style-type: none"> Improve the recycling efficiency of building materials, strengthen the recycling of building materials, and promote the reduction of construction waste. By changing the traditional landfill treatment method, the thermal energy and electric energy of biomass material combustion can be rationally utilized.

results of the building-embodied carbon in the analysis of key scenarios to determine the policy implications. For example, scenarios can be set to assess the life-cycle carbon reduction potential of replacing building materials with low-carbon materials, such as novel biomass materials. The results can be used as a reference for the formulation of low-carbon building policies.

4. Conclusions and life cycle-based policy implications

4.1. Conclusions

This paper account for the embodied carbon emissions in buildings in 2020 for the Guangdong-Hong Kong Macau Greater Bay Area in China (GBA). We integrated NLT data and building material flows analysis to calculate and spatialize the newly consumed building MS. Based on the MS data, we further applied life cycle assessment to assess the embodied carbon in the buildings. The results revealed over 497 million tons of newly generated MS in

2020, which generated about 163 million tons embodied carbon emissions.

Throughout the various phases of its life cycle, MS exhibits distinct levels of embodied carbon emissions. Specifically, during the “Building materials product stage,” the emissions amount to 100.74 million tons, followed by 12.85 million tons in the “Construction stage,” 39.05 million tons in the “Use stage,” 2.71 million tons in the “Demolition stage,” and 7.77 million tons in the “End of life stage.” These life cycle-based quantitative emissions were valuable to enlighten further life cycle-based policy implications.

4.2. Life cycle-based policy implications

Finally, based on the embodied carbon, and the critical circular economy implications, the highlighted life cycle-based policies are proposed, discussed, and summarized in Table 8. The calculation of embodied carbon has highlighted the importance of green and low embodied carbon materials, carbon audit (particularly scope-3

emission accounting) using the life cycle information, updating the current certification system (net zero building calls for new attention to how to incorporate life cycle & embodied carbon emissions into current green building certification system) using the embodied carbon, how to reduce construction related emissions from the perspective of carbon offset (e.g., Japan highlights their focuses to carbon absorbed in concrete and China highlights to carbon sink measures), and, how to make the better use of new policy analytical tools like LCA and embodied carbon emission accounting with emerging technologies (like block chains) to strongly support these decision make efforts.

Based on the policy highlights from each life cycle phase mentioned in the Table 8, the following policies can be implemented to reduce carbon emissions throughout the life cycle of buildings:

(i) According to the results, the buildings produce the most embodied carbon emissions (100.74 Mt) at building materials product stage. During this stage, it is important to prioritize the use of renewable resources with lower or even negative carbon emissions. Promoting the recycling of demolition waste and reducing raw material consumption through reuse and recycling are essential. Designing buildings with creative approaches that incorporate more renewable materials is another effective measure. In addition, the application of digital technologies, such as integrated blockchain and carbon footprint tracking, is a reliable way to track carbon emissions in the supply chain.

(ii) In the transportation phase, prioritizing the use of renewable resources can significantly reduce the embodied carbon emissions stemming from fossil fuel consumption. Implementing waste-to-energy solutions can also help reduce fossil fuel consumption in transportation.

(iii) During the construction and renovation process, prioritizing the use of renewable resources is vital. This includes incorporating more renewable materials and renewable energy sources. Developing and promoting prefabricated buildings can contribute to reducing embodied emissions in this phase.

(iv) In the use stage, promoting the adoption of renewable energy sources and materials helps to minimize operational carbon emissions. Emphasizing reuse, recycling, and circularity of building parts further contributes to carbon reduction efforts.

(v) During maintenance, refurbishment, and replacement activities, promoting the use of renewable energy and materials in green interior decoration is crucial. Ensuring that short-lived components can be repaired or replaced helps extend the life cycle of buildings. Encouraging the green transformation of existing buildings, including the renovation of old residential areas in cities and towns and dilapidated houses in rural areas can lead to significant resource savings.

(vi) During the deconstruction and demolition phase, extending the lifetime of buildings is crucial for reducing environmental impact per unit time. Developing novel circular business models involving constructors, contractors, and recyclers can enhance the value chain in the circular economy.

(vii) In waste disposal and recycling, improving the recycling efficiency of building materials and promoting the reduction of construction waste are vital. By shifting from traditional landfill treatment methods, rational utilization of thermal energy and electric energy from biomass material combustion can be achieved.

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CRedit authorship contribution statement

Hanwei Liang: Methodology, Supervision, Writing – original draft, Writing – review & editing. **Xin Bian:** Methodology, Data curation, Formal analysis, Investigation, Writing – original draft. **Liang Dong:** Conceptualization, Methodology, Supervision, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gsf.2023.101760>.

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