

Article

Research on Accounting and Transfer Pathways of Embodied Carbon Emissions from Construction Industry in China

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Abstract: In recent years, China has taken the issue of excessive CO₂ emissions very seriously, and the construction industry is a key sector in its efforts to reduce carbon emissions. This research constructed a multi-regional input-output (MRIO) model to estimate the carbon emissions from the construction industry, and analyze the spatial and industrial transfer pathways of the carbon emissions from the inter-regional construction industry. The following findings were obtained in this study: (1) Based on the consumption-side accounting, the amount of embodied carbon emissions that were switched to China's construction industry massively exceeded that of embodied carbon emissions that were transferred from it. (2) A large amount of embodied carbon emissions was transferred from the energy industry, heavy industry, and manufacturing in the resource-rich region to the construction industry in the economically developed coastal region and the southwest region with a defective industrial structure. The above findings provided a theoretical basis for the allocation of construction industry's carbon emission reduction responsibilities. Accordingly, this paper put forward policy suggestions that could optimize the carbon emission reduction plans in the construction industry.

Keywords: construction industry; embodied carbon emissions; MRIO model; spatial transfer; industrial transfer



Citation: Qi, Y.; Xia, Y. Research on Accounting and Transfer Pathways of Embodied Carbon Emissions from Construction Industry in China. *Sustainability* **2022**, *14*, 15165. <https://doi.org/10.3390/su142215165>

Received: 11 October 2022

Accepted: 14 November 2022

Published: 16 November 2022

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1. Introduction

The increase in greenhouse gas emissions in recent years has caused many environmental problems, which not only seriously affect the ecological environment, but also pose a huge challenge to the sustainable development of the national economy. As the world's largest CO₂ emitter, China's government committed, in the Paris Agreement, to reduce CO₂ emissions per unit of GDP by 60–65% by 2030 compared to 2005, and to peak total CO₂ emissions. The task of carbon emissions reduction is generally allocated to provinces or sectors using production-based accounting methods [1]. In fact, in the process of regional economic integration, trade separates the producers and consumers of commodities, resulting in the transfer of carbon emissions and responsibility shifting for carbon emission reduction. The construction industry is considered by academics as one of the primary sources of embodied carbon emissions. The embodied carbon emissions from the construction industry accounted for 24.33% of China's total carbon emissions [2]. And the upstream and downstream related sectors are the primary sources of large-scale carbon emissions. Qi et al. [2] showed that 98% of the construction industry's responsibility for embodied carbon emission reduction came from its associated sectors. Still, the production-based accounting method neglects the indirect emissions embodied in the supply chain with information linkage [3]. Therefore, the policy that allocates the responsibilities for carbon emission reduction based on inter-regional carbon emission transfer has received more and more attention from all relevant stakeholders [4]. It can formulate the responsibilities of regions and sectors more rationally from the perspective of consumer responsibility. Moreover, the uneven distribution of natural resources, different industrial structures

and varying levels of economic development in each province of China directly affect the development of the regional construction industry, meaning that carbon emissions from China's construction industry vary greatly from region to region. When facing the complex carbon emission situation in China's construction industry, effectively allocating the carbon emission reduction responsibilities of the construction industry in each region, as well as the carbon emission reduction responsibilities of the construction industry and related sectors, requires that the inter-industrial and inter-regional carbon emission transfer in the construction industry is clarified.

The current studies on carbon emission in China's construction industry mostly use cross-sectional data about annual carbon emissions from the regional construction industry to reflect the total energy consumption and carbon emissions, and to provide a basis for the government to formulate energy conservation and carbon emission reduction policies [5]. Otherwise, they focus on the spatial and temporal differences in carbon emissions in the construction industry and predict the carbon emission trends. Li et al. [6] accounted for carbon emissions from 2000 to 2017 in the operational phase of buildings according to province, and analyzed the regional differences in carbon emissions from buildings in detail. Fan et al. [7] used spatial autocorrelation and kernel density estimation to portray and analyze the spatial and temporal characteristics of carbon emissions in 30 provinces. Zhang [8] revealed the dynamic change pattern of carbon emissions in 28 cities. In general, existing research on carbon emissions in China's construction industry emphasizes the spatial distribution characteristics of the construction industry between regions, relatively neglecting the mutual influence and interaction between its upstream and downstream sectors. Meanwhile, most studies only calculate direct carbon emissions from the construction industry, and only a small number of studies have analyzed the embodied carbon emissions due to carbon emission transfer. Qi et al. [2] accounted for the embodied carbon emissions of China's construction industry based on I-O theory and predicted the evolution of the embodied carbon emissions of the construction industry during 2011–2020; Zhu Chen et al. [9] constructed three extended analytical models with six indicators to discuss the direct and indirect carbon emissions in the construction industry. There are few special studies on carbon emission transfer in the construction industry and, more often than not, the construction industry is mentioned in the analysis of the characteristics of carbon transfer from trade.

In terms of research methods, the environmentally extended input-output (EEIO) analysis developed a mainstream analytical method for the quantitative study of embodied carbon emission transfer [10–12], which can integrate the spatial transfer and industrial transfer of carbon emissions into an overall analytical framework and combine two dimensions to comprehensively analyze the transfer pathways. The application of input-output analysis methods has gone through a process of continuous improvement from a simple single-region input-output model (SRIO), to an embodied carbon emission model from a bilateral trade perspective (EEBT), to a multiregional input-output model (MRIO) from a multilateral trade perspective [13]. Peter et al. [14] proposed a collaborative approach to carbon emission reduction by simulating different carbon emission reduction policies based on the carbon emissions of 87 countries in international trade in 2001. Cellura M et al. [15] applied an EIO-LCA model to assess the energy and environmental benefits arising from the Italian policy of tax deduction for the energy retrofit actions of buildings. Hu [13] constructed the MRIO model to analyze the spatial and industrial transfer pathways of China's embodied carbon emissions among the industrial chain in provincial-level administrative regions. Yan et al. [16] measured the scale of embodied carbon emissions transfer between regions in China with the MRIO model. In contrast, the MRIO model can cover the indirect effects generated by production activities in the supply chain and is more suitable for measuring the spillover of carbon emissions from the construction industry.

The above analysis shows that the existing relevant research fails to grasp the law of the spatial and industrial transfer of embodied carbon emissions in the construction

industry, and thus fails to clearly define the responsibility for carbon emission reductions in the construction industry. To provide a basis for the allocation of responsibility for carbon emission reduction and to promote the low-carbon transformation of the construction industry, this research constructed a multi-regional input-output (MRIO) model from the spatial and industrial dimensions. Then, the model was applied using the data from the CEADs database to measure the embodied carbon emission transfer among 27 industry sectors in 30 provincial-level administrative regions in China. Based on the calculation results, this paper analyzed the distribution characteristics and transfer pathways of embodied carbon emissions in the construction industry, and provides theoretical support and policy references for carbon emission reduction in the construction industry.

2. Research Method, Model, and Data

2.1. Research Method

The multi-regional input-output model is an input-output model developed for multiple regions and is a component of the overall input-output model. It reflects the production technology linkage and the comprehensive balance of supply and demand among relevant sectors within multiple regions, and indicates the generation and distribution of national income in the region, which can then forecast and analyze various technical and economic issues within regions or between one region and the whole. The basic form of the non-competitive MRIO model is as follows [17]:

$$X = AX + Y - X^m \quad (1)$$

where X is a column vector of total output composed of n rows; A is the $(n \times n)$ matrix of technical coefficient whose elements a_{ij} represent the direct consumption coefficient of sector j to sector i ; Y is the column vector (n rows) of final demand and X^m is the column vector (n rows) of imports.

Equation (2) is the result of the factorization of Equation (1). $L = (I - A)^{-1}$ is called the Leontief inverse matrix. The elements L_{ij} denote the complete consumption of total output of sector i by sector j .

$$X = (I - A)^{-1}Y \quad (2)$$

In the production process, a large number of direct carbon emissions from many industry sectors are not only used to meet the demand for final products in their sectors but also flow into other sectors in the form of embodied carbon emissions, along with the industrial chain and intermediate products [18]. To calculate the embodied carbon emission, the direct carbon emission coefficient e is introduced to establish the link between carbon emission and input-output model. See Equation (3), below,

$$T = e(I - A)^{-1}Y \quad (3)$$

where $e(I - A)^{-1}$ is the embodied carbon emission coefficient that indicates the direct and indirect carbon emissions generated by a sector to provide one unit of the final demand product [13].

2.2. Measuring Model

Referring to the model construction method of Shi et al. [19], the equilibrium relationship between supply and demand in region r is as follows:

$$X^r = A^{rs}X^r + Y^{rs} + EX^r - IM^{rs} \quad (4)$$

where X^r represents the output array for each industry sector in region r ; A^{rs} is the direct consumption coefficient matrix; Y^{rs} refers to the final demand array; EX^r is the export matrix; IM^{rs} is the import array.

To exclude the effect of these imports, the import coefficient matrix $\hat{M}$ is introduced. The import coefficient is the ratio of the volume of imported products to total domestic demand. After excluding imports, if $A \neq I$, and $I - A$ is invertible, Equation (4) can be rewritten as follows:

$$X^r = [I - (I - \hat{M})A^{rs}]^{-1}[(I - \hat{M})Y^{rs}] \quad (5)$$

where $L = [I - (I - \hat{M})A^{rs}]^{-1}$ refers to the Leontief inverse matrix after excluding the effect of imports.

Multiplying the above Leontief inverse matrix with the direct carbon emission factor yields the full carbon emission coefficient matrix. See Equation (6), below,

$$C^{rs} = D^{rs}[I - (I - \hat{M})A^{rs}]^{-1} \quad (6)$$

$$D_i^r = CE_i/x_i^r \quad (7)$$

where C^{rs} represents the inter-regional carbon emission coefficient matrix, and D_i^r is the direct carbon emission factor.

Finally, the carbon emission coefficient matrix is multiplied with the final consumption matrix, excluding the effect of imports, to obtain the embodied carbon emission transfer matrix between regions and industries. See Equation (8), below.

$$T^{rs} = C^{rs}[(I - \hat{M})Y^{rs}] \quad (8)$$

In the calculation, the embodied carbon emission transferred from region r to region s was the portion of carbon emissions from region r caused by providing products and services to region s. The embodied carbon emission transferred from region s in region r referred to the portion of carbon emissions in region s caused by providing products and services to region r [13].

2.3. Data Sources

The inter-regional input-output data were obtained from China's 2012 MRIO for 30 provinces and 30 sectors compiled by Mi et al. [20], which belongs to the CEADs database. The 30 industry sectors in the table were combined and organized into 27 sectors in this research. As data from Tibet, Hong Kong, Macao, and Taiwan are not easily available, these regions were not included in the input-output table. Based on the sectoral method used to calculate carbon emissions in the IPCC guidelines [21], this paper selected eight fossil energy sources: coal, coke, crude oil, kerosene, diesel, gasoline, fuel oil, and natural gas [16], and used the sectoral method for calculations See Equation (9), below,

$$CE_i = \sum_k CE_{ik} = \sum_k AD_{ik} \times NCV_k \times CC_k \times O_{ik} \times \frac{44}{12} \quad (9)$$

where CE_i refers to the total direct carbon emissions in sector i ; AD_{ik} represents the consumption by fossil fuels in sector i , based on the Chinese provincial energy inventory from the CEADs database [22–25]; NCV_k refers to the net caloric value, which is the heat value produced per physical unit of fossil fuel combustion, with data from the China Energy Statistics Yearbook 2013; CC_i and O_{ik} are the carbon content per unit of calorific value and oxygenation efficiency, mainly referring to the IPCC guidelines [21] and Lv et al. [26].

3. Results and Analysis

3.1. Transfer of Embodied Carbon Emissions in Inter-Regional Construction Industry

The total amount of embodied carbon emissions transferred from the construction industry in China in that year was 59.791 million tons, and the total amount of carbon emissions that switched to the construction industry was 1229.1071 million tons. The amount of embodied carbon emissions transferred from the construction industry in each provincial-level administrative region was smaller than the amount of that was switched

to the construction industry. Among them, the top six provincial-level administrative regions in terms of embodied carbon emissions transferred from the construction industry were Hubei, Zhejiang, Inner Mongolia, Hunan, Shandong, and Tianjin, with a total of 26,516,200 tons of embodied carbon emissions being transferred, accounting for 44.35% of the total carbon emissions transferred from the country's construction industry. The top six provincial-level administrative regions in terms of the embodied carbon emissions that switched to the construction industry were Jiangsu, Shandong, Hebei, Liaoning, Sichuan, and Hubei, with a total of 457,754,400 tons of embodied carbon emissions being transferred there, accounting for 37.24% of the total amount of embodied carbon emissions that switched to the construction industry (see Table 1).

Table 1. Embodied carbon emissions transfer from the inter-regional construction industry in China.

Provincial-Level Administrative Region	Transfer Out (10 ⁴ t)	Transfer In (10 ⁴ t)	¹ Net Carbon Emission Transfer (10 ⁴ t)
Beijing	8.22	2374.56	−2366.34
Tianjin	350.10	2347.15	−1997.05
Hebei	185.33	8203.35	−8018.02
Shanxi	140.84	3482.08	−3341.25
Inner Mongolia	443.91	2843.29	−2399.38
Liaoning	240.16	6532.85	−6292.70
Jilin	143.99	3465.62	−3321.63
Heilongjiang	21.84	3037.66	−3015.82
Shanghai	205.16	1768.92	−1563.76
Jiangsu	140.45	9542.80	−9402.35
Zhejiang	507.14	5256.71	−4749.57
Anhui	203.96	3902.41	−3698.44
Fujian	137.53	3023.71	−2886.18
Jiangxi	37.53	3394.69	−3357.16
Shandong	365.42	8932.86	−8567.44
Henan	161.26	4239.28	−4078.02
Hubei	601.04	6217.29	−5616.25
Hunan	384.00	5116.48	−4732.48
Guangdong	196.11	3025.68	−2829.57
Guangxi	15.68	3724.26	−3708.58
Hainan	34.56	1003.03	−968.47
Chongqing	187.62	5981.39	−5793.77
Sichuan	270.39	6346.28	−6075.89
Guizhou	101.36	2536.23	−2434.86
Yunnan	261.66	4882.81	−4621.15
Shaanxi	271.15	3747.80	−3476.65
Gansu	139.12	2107.68	−1968.56
Qinghai	39.79	848.52	−808.73
Ningxia	74.56	1168.68	−1094.12
Xinjiang	109.22	3856.62	−3747.41

¹ Net carbon emission transfer = Transfer out − Transfer in.

From the perspective of the inter-industrial transfer of embodied carbon emissions, other sectors transferred a total of 106,763.48 million tons of embodied carbon emissions to the construction industry, of which the top six industry sectors, in order of transfer volume, were metallurgy (D14), electricity and heat production and supply (D22), non-metal products (D13), coal mining (D2), chemical industry (D12), and petroleum refining, coking, etc. (D11), with the total outward transfer accounting for 93.87% of the total transfer of 26 sectors. However, the embodied carbon emissions that were transferred from the construction industry to the other 26 sectors were only 1,098,600 tons, of which only the amount of embodied carbon emissions transferred from other services (D26) to the construction industry was smaller than the amount of that was transferred from the construction industry to other services (D26) (see Table 2).

Table 2. Embodied carbon emissions transfer from other sectors to the construction industry.

¹ Industry Sector Codes	Transfer Out (10 ⁴ t)	Transfer In (10 ⁴ t)	Net Carbon Emission Transfer (10 ⁴ t)
D1	1070.63	2.57	1068.06
D2	10,017.77	0.47	10,017.30
D3	1051.80	0.03	1051.78
D4	583.80	0.02	583.78
D5	1141.83	0.12	1141.71
D6	377.46	6.73	370.72
D7	142.41	1.04	141.38
D1	1070.63	2.57	1068.06
D8	51.10	3.20	47.89
D9	295.07	0.97	294.10
D10	412.46	0.72	411.74
D11	3236.16	0.51	3235.66
D12	5977.82	3.60	5974.22
D13	20,497.38	1.30	20,496.09
D14	39,938.39	0.63	39,937.76
D15	313.19	2.11	311.08
D16	282.28	5.58	276.70
D17	62.70	7.72	54.97
D18	148.96	3.46	145.50
D19	19.07	2.19	16.87
D20	11.34	0.30	11.04
D21	80.47	0.24	80.22
D22	20,550.32	1.60	20,548.72
D23	134.21	0.33	133.88
D24	296.75	7.78	288.98
D25	52.39	9.08	43.31
D26	17.74	47.57	−29.84

¹ Industry sector codes and meanings: agriculture (D1), coal mining (D2), petroleum and gas (D3), metal mining (D4), nonmetal mining (D5), food processing and tobaccos (D6), textile (D7), clothing, leather, fur, etc. (D8), wood processing and furnishing (D9), paper making, printing, stationery, etc. (D10), petroleum refining, coking, etc. (D11), chemical industry (D12), nonmetal products (D13), metallurgy (D14), metal products (D15), general and specialist machinery (D16), transport equipment (D17), electrical equipment (D18), electronic equipment (D19), instrument and meter (D20), other manufacturing (D21), electricity and hot water production and supply (D22), gas and water production and supply (D23), transport and storage (D24), wholesale, retailing, hotel, and restaurant (D25), other services (D26).

3.2. Distribution Characteristics of Embodied Carbon Emission in Inter-Regional Construction Industry

According to Table 1, the provincial-level administrative regions with a mass of embodied carbon emissions being transferred from the construction industry can be roughly divided into three types: resource-rich, good industrial base, and good manufacturing bases, such as Hubei, Zhejiang, Inner Mongolia, Hunan, and Shandong. Most provincial-level administrative regions with high outward-transfer ratios are resource-rich and have high economic aggregate types. However, the provinces and municipalities with good manufacturing bases but a small economic aggregate, whose products mainly serve the local market, do not have high outward-transfer ratios. The provincial-level administrative regions with a mass of embodied carbon emissions that were switched to the construction industry include Jiangsu, Shandong, Hebei, Liaoning, Sichuan, etc. The provincial-level administrative regions with high inward-transfer ratios, such as Beijing, Guangxi, Heilongjiang, and Jiangxi, reflect the following significant features: First, the provincial-level administrative regions with a faster development of the construction industry and considerable-scale manufacturing industry have more embodied carbon emissions that switched to the construction industry. Second, Jiangxi, Hainan, Guangxi, and other provincial-level administrative regions with a more backward development of the construction industry, and Heilongjiang, Liaoning and other provincial-level administrative regions

with rich resources but an incomplete industrial structure, have a higher proportion of embodied carbon emission switched to their construction industry.

Among the eight major economic zones, the three zones with a mass of embodied carbon emissions being transferred from the construction industry were the middle reaches of the Yellow River economic zone, the middle reaches of Yangtze River economic zone, and the northern coastal economic zone. The three zones with a mass of embodied carbon emissions that switched to the construction industry were the eastern coast economic zone, the southwestern economic zone, and the northern coastal economic zone (see Table 3).

Table 3. Embodied carbon emission transfer of construction industry in eight major economic zones.

¹ Economic Zone	Transfer Out (10 ⁴ t)	Transfer In (10 ⁴ t)	Net Carbon Emission Transfer (10 ⁴ t)
The northeast economic zone	1.18	2748.02	−2746.84
The northern coastal economic zone	2.40	4432.12	−4429.72
The eastern coastal economic zone	1.91	10,598.80	−10,596.89
The southern coastal economic zone	0.59	2748.73	−2748.14
The middle reaches of Yellow River economic zone	3.58	3740.44	−3736.86
The middle reaches of Yangtze River economic zone	3.34	4425.35	−4422.01
The southwest economic zone	1.78	5029.88	−5028.09
The northwest economic zone	0.78	2166.20	−2165.42

¹ Eight major economic regions: the northeast economic zone includes Heilongjiang, Jilin, and Liaoning; the northern coastal economic zone includes Beijing, Tianjin, Hebei, and Shandong; the eastern coastal economic zone includes Shanghai, Jiangsu, and Zhejiang; the southern coastal economic zone includes Fujian, Guangdong, and Hainan; the middle reaches of Yellow River economic zone includes Shaanxi, Shanxi, Henan, and Inner Mongolia; the middle reaches of Yangtze River economic zone includes Hubei, Hunan, Jiangxi, and Anhui; the southwest economic zone includes Yunnan, Guizhou Sichuan, Chongqing, Guangxi; the northwest economic zone, including Gansu, Qinghai, Ningxia, Xinjiang, Tibet (this research does not count).

4. Discussion

4.1. Spatial Transfer Pathways of Embodied Carbon Emissions from the Construction Industry

The embodied carbon emissions from the construction industry were transferred on a large scale within the central-eastern region of China. With Jiangsu and Zhejiang as the center, the surrounding provinces and municipalities formed the region with the largest volume of embodied carbon emissions from the construction industry and the largest scale of transfer in China (see Figure 1). The large-scale transfer was mainly between provincial-level administrative regions with abundant energy reserves and good industrial bases and those with a large volume of the construction industry. Take Jiangsu province, the province with the largest scale of embodied carbon emissions that switched to the construction industry, as an example: the embodied carbon emissions that switched to the construction industry of Jiangsu from metallurgy, coal mining, and the nonmetal products of Anhui province were 1,990,675.23 tons, 1,913,519.21 tons and 1,538,526.18 tons, respectively, accounting for 25.03%, 24.06% and 19.34% of the total amount that switched to the construction industry of Jiangsu from Anhui. The embodied carbon emissions that switched to the construction industry of Jiangsu from metallurgy, coal mining, and gas and water production and supply of Henan province were 2,760,306.33 tons, 1,398,864.37 tons and 1,288,419.83 tons, respectively, accounting for 34.90%, 17.69% and 16.29% of the total amount that switched to the construction industry of Jiangsu from Henan.

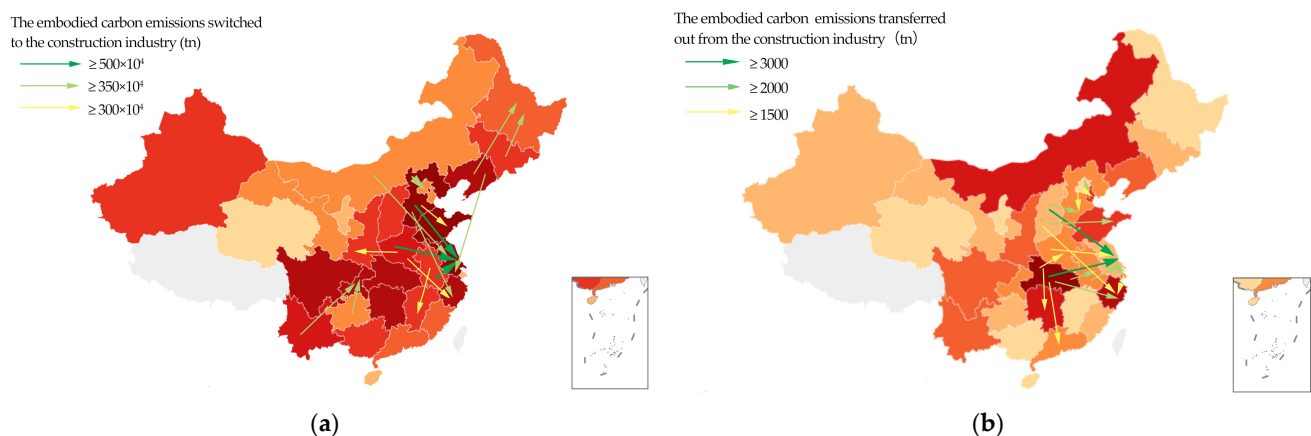


Figure 1. Embodied carbon emission transfer pathways in inter-regional construction industry of China. (a) The spatial transfer pathways that the embodied carbon emissions switched to the construction industry; (b) The spatial transfer pathways that the embodied carbon emissions transferred from the construction industry.

The Beijing–Tianjin–Hebei region also transferred more within the region, among which Tianjin’s construction industry transferred 1062.01 tons and 527.46 tons of embodied carbon emissions to Beijing’s other service and construction industry, respectively, while Beijing’s construction industry transferred 549.69 tons and 485.36 tons of embodied carbon emissions to Tianjin’s construction industry and other services, respectively, and Beijing’s construction industry and Tianjin’s construction industry consumed 4,934,200 tons and 1,574,300 tons of embodied carbon emissions from Hebei’s metallurgy, respectively. The transfer pathways mainly showed that Tianjin and Beijing’s construction industries transferred a large amount of the embodied carbon emissions to each other, and Hebei transferred a large amount of embodied carbon emissions to Beijing’s construction industry.

Among the eight major economic zones, the construction industry in all six zones, except the southern coastal economic zone, consumed a large number of the embodied carbon emissions from the middle reaches of Yellow River, with the construction industry in the eastern coastal economic zone consuming the most carbon emissions. The construction industry in the eastern coastal economic zone not only consumed many of the carbon emissions from the middle reaches of Yellow River, it also consumed a large number of embodied carbon emissions from the northeast economic zone, the northern coastal economic zone, the middle reaches of Yangtze River, and the southwest economic zone. The construction industry in the middle reaches of Yangtze River and in the southwest economic zone consumed a large amount of the embodied carbon from each other’s zones, and the embodied carbon emissions from the northern coastal economic zone both accounted for a high proportion of the total embodied carbon emissions that switched to the construction industry in both zones. Large-scale carbon emissions transfer also occurred between the construction industry in the middle reaches of Yellow River and the northern coastal economic zone, while the construction industry in the middle reaches of Yellow River consumed 12,209,700 tons of the embodied carbon emissions from the northern coastal economic zone (see Table 4). As inter-provincial trade between the construction industry and its upstream and downstream sectors is more likely to reach economic cooperation between nearby provincial-level administrative regions, the embodied carbon emission transfer pathways in the construction industry also exist, mostly within the economic zones, with obvious geographical proximity effects.

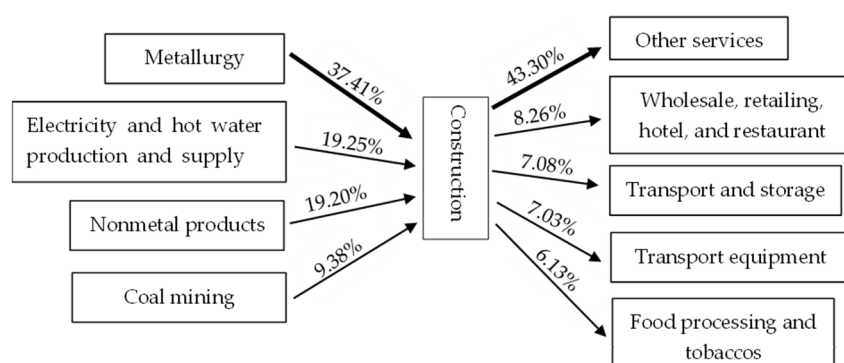
Table 4. Embodied carbon emission transfer pathways of the construction industry in eight major economic zones.

	Construction Industry in the Northeast	Construction Industry in the Northern Coast	Construction Industry in the Eastern Coast	Construction Industry in the Southern Coast	Construction Industry in the Middle Reaches of Yellow River	Construction Industry in the Middle Reaches of Yangtze River	Construction Industry in the Southwest	Construction Industry in the Northwest
The northeast	—	−827.94	−1192.24	−191.02	−447.86	−365.65	−484.74	−290.34
The northern coast	−744.62	—	−1865.62	−339.81	−1220.97	−708.03	−747.84	−340.72
The eastern coast	−185.10	−208.51	—	−106.20	−232.37	−479.49	−252.19	−96.52
The southern coast	−88.58	−103.20	−353.65	—	−129.08	−217.33	−372.09	−78.80
The middle reaches of Yellow River	−852.89	−2091.63	−2742.81	−490.36	—	−1490.49	−1561.32	−768.65
The middle reaches of Yangtze River	−244.30	−380.41	−2371.35	−477.95	−485.06	—	−842.71	−201.37
The southwest	−322.90	−407.93	−1278.01	−901.78	−655.96	−814.70	—	−389.03
The northwest	−308.45	−410.10	−793.21	−241.02	−565.56	−346.32	−767.20	—

The value in the table represents the net transfer of embodied carbon emissions from the construction industry. Net carbon emission transfer = transfer out − transfer in, unit: million tons.

4.2. Industrial Transfer Pathways of Embodied Carbon Emissions from the Construction Industry

Figure 2 represented the transfer pathways between the construction industry and the four major embodied carbon emission inward-transfer sectors and the five major embodied carbon outward-transfer sectors. The sectors that transfer embodied carbon emissions to the construction industry were both energy-intensive and carbon-intensive, such as metallurgy and coal mining industries. The embodied carbon emissions transferred from the metallurgy to the construction industry accounted for 37.41% of the total amount that switched to the construction industry, and the embodied carbon emissions transferred from the electricity and hot-water production and supply accounted for 19.25% of the total amount that switched to the construction industry. The embodied carbon emissions from the construction industry were mainly transferred to the other services, with the embodied carbon emissions switched to this sector accounting for 43.30% of the total amount transferred from the construction industry. Compared with the amount of embodied carbon emissions transferred from the construction industry, the amount that switched to the construction industry was tremendous. A large number of embodied carbon emissions were transferred from high-carbon sectors in regions that are energy-rich and have developed heavy industries to the construction industry in economically developed regions and regions with an incomplete industrial structure. The construction industry, as a carbon consumer, should bear part of the energy-intensive sectors' responsibility for carbon emission reductions.

**Figure 2.** Main transfer pathways of embodied carbon emission between the construction industry and other sectors.

5. Conclusions

This research used the multi-regional input-output (MRIO) model to establish the embodied carbon emission transfers between the construction industry and another 26 sectors in 30 provincial-level administrative regions of China, and then studied and analyzed the spatial transfer pathways and industrial transfer pathways. The main findings of this research are as follows.

The construction industry is one of the major carbon-consuming sectors in China. Due to the effects of geographical proximity and complementary industrial structure, the large-scale embodied carbon emission transfers of the construction industry in China occurred in the region consisting of the nearby provinces and municipalities with a high economic correlation. With Jiangsu and Zhejiang as the center, the surrounding provinces and municipalities formed the region with the largest volume of embodied carbon emissions from the construction industry and the largest scale of transfer in China. Within these regions, the energy-intensive industries in resource-rich provinces or municipalities were mostly carbon producers, and the construction industries in economically developed provinces or municipalities were mostly carbon consumers. Meanwhile, the embodied carbon emissions from the construction industry were mainly consumed by the sector, other service. From the above spatial transfer characteristics and industrial transfer characteristics of the embodied carbon emissions in the construction industry, we can see that the allocation of responsibility for carbon emission reductions in China's construction industry involves many sectors and the inter-regional allocations are complex. According to the consumption-based accounting principles, the construction industry should bear part of the energy-intensive industries' responsibility for carbon emission reductions, and the sector, other services, should bear part of the construction industry's responsibility for carbon emission reductions. Regions with a more developed construction industry should take on some responsibility for regions that supply them with energy, thus reducing pressure on the producers.

In the "Action Plan for Carbon Dioxide Peaking Before 2030", it is mentioned that formulating local peaking carbon dioxide emissions plans through coordination between central and local authorities, and the people's governments in provinces, autonomous regions, and municipalities should consider the whole-of-nation approach. Combined with the findings of this paper, three carbon emission reduction policy suggestions are proposed for China's construction industry. First, with full consideration of the role of each provincial-level administrative region in the national economic system and the distribution characteristics of the construction industry, the government should develop a cross-regional collaborative carbon emission reduction strategy. They can first develop regional collaborative carbon emission reduction policies for the construction industry in central and developed coastal regions, the most active regions of carbon emission transfer, and then extend the experience to the whole country after the carbon emission reduction measures have matured. For instance, in the Beijing–Tianjin–Hebei region, Beijing's construction industry and Tianjin's construction industry consumed 4,934,200 tons and 1,574,300 tons of embodied carbon emissions from Hebei's metallurgy, respectively. The three local governments can break down the amount of carbon emissions transferred according to their value-added ratio or agreement. Based on the results, the carbon emission reduction responsibilities are then rationally allocated to producers, i.e., metallurgy in Hebei, and consumers, i.e., the construction industry in Beijing and Tianjin. Second, according to the industrial transfer pathways, the major embodied carbon emission inward-transfer sectors for the construction industry are upstream industry sectors. Therefore, the construction industry and upstream sectors should work together to reduce carbon emissions and reduce carbon emissions intensity of the industry chain, centered on the construction industry. In particular, the construction industry should collaborate with metallurgy, electricity and hot-water production and supply, nonmetal products, and coal mining to improve energy efficiency and optimize the energy structure in the sectors that produce components and building materials. Meanwhile, the practice indicates that the prefabricated building has significant advantages in conserving energy and reducing waste of materials, thus reducing carbon emissions, so the government should encourage it. Third, the construction industry should introduce some high level of technologies to rationally allocate all kinds of resources and strengthen the management of each link in the whole lifecycle. Raising carbon emission standards is also a way to promote carbon emission reduction in the construction industry. These measures will help China reach the goal of an

18% drop in carbon dioxide emissions per unit of GDP by 2025, compared to 2020, laying a solid foundation for the peak in carbon dioxide.

This study offsets the poor coverage of industry sectors in existing studies on the carbon emission transfer of the construction industry and lays a theoretical foundation for the government to allocate the responsibility for carbon emission reductions and reform the construction industry policies. The data used for this study are difficult to collect, and there are differences in the statistical caliber. Further studies will look for data from recent years, enhancing the timeliness of the studies on carbon emission transfers from the construction industry.

Author Contributions: Conceptualization, Y.Q. and Y.X.; methodology, Y.Q.; software, Y.X.; validation, Y.Q. and Y.X.; formal analysis, Y.X.; investigation, Y.X.; resources, Y.Q.; data curation, Y.X.; writing—original draft preparation, Y.X.; writing—review and editing, Y.Q. and Y.X.; visualization, Y.X.; supervision, Y.Q.; project administration, Y.Q.; funding acquisition, Y.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Beijing Natural Science Foundation (8202018).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: All the authors thank editors and anonymous reviewers for their constructive comments and suggestions for improving the quality of this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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