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Nation-based accounting method to identify key sectors on embodied carbon contribution using network of networks model

1st Feng An
School of Humanities and Economic M anagement
China University of Geosciences
Beijing, China
af@cugb.edu.cn

2nd Xiangyun Gao*
School of Humanities and Economic M anagement
China University of Geosciences
Beijing, China
gxy5669777@126.com

3nd Nanfei Jia
School of Humanities and Economic M anagement
China University of Geosciences
Beijing, China
18600121158@163.com

Abstract—To better account the contribution of various industries around the world to embodied carbon emissions, this study proposes a new accounting method from a global perspective. Unlike traditional accounting methods, our proposed accounting method considers all industries in a country as a whole. The embodied carbon emissions of the country are first accounted for and distributed to each sector within the country according to the contribution of each industry to the country's inherent carbon emissions. To achieve this goal, we propose a network model and algorithm for the global embodied carbon network. Based on our proposed models and algorithms, we recalculated the contribution of inherent carbon emissions in various industries. Unlike traditional accounting results, we find that supportive industries such as education, health care, and public services contribute a lot to embodied carbon emissions. Not just embodied carbon-related research, our accounting methods, and NoN models provide a model basis for other research, such as international trade and global input and output.

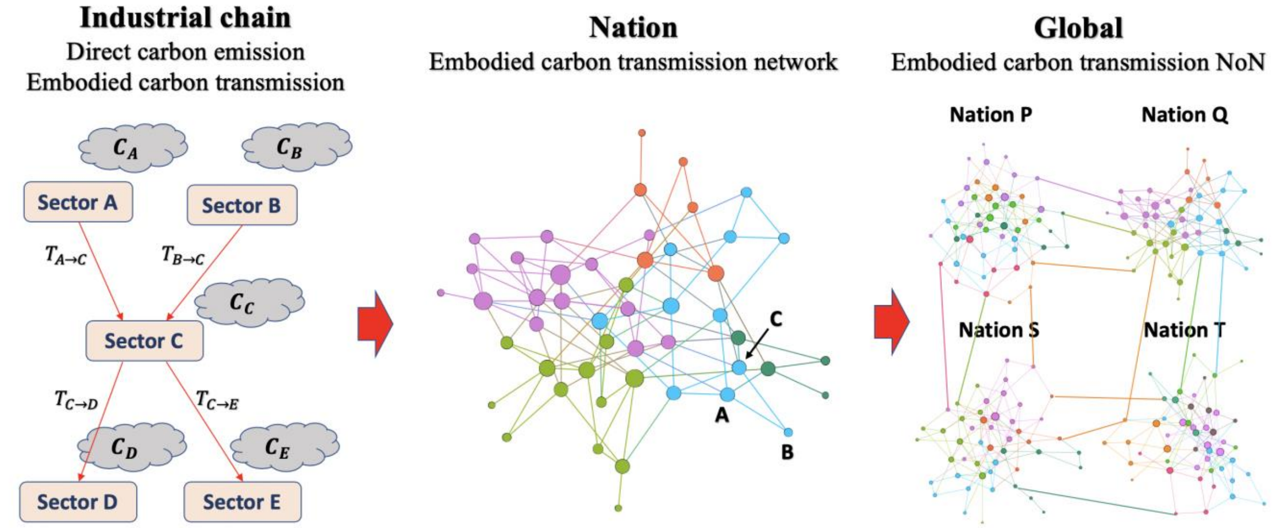
Keywords—embodied carbon, key sectors, complex networks, network of networks.

I. INTRODUCTION

Reducing carbon emissions is one of the most important measures to reduce planetary warming and to improve our environment [1-9]. Precisely accounting for the carbon emissions contributions of each sector is fundamental for effective carbon-reduction policy making [10-21]. There are also many different ways that sectors contribute to carbon emissions: for example, through direct carbon dioxide emissions into the atmosphere during production or through embodied carbon transmission as part of downstream product flow in the production chain and market. Previous studies accounting for sectors' carbon emissions have mainly focused on two levels: the 'industrial chain level' and 'nation level', which are shown in Fig. 1 [10, 11, 14, 17, 22-27]. The 'industrial chain level' involves accounting for sectors' direct carbon emissions amount and embodied carbon transmission amount based on their input-output amount and carbon consumption coefficient. The 'nation level' involves constructing an embodied carbon transmission network and detecting the carbon emissions transmission amount of each sector from the other sectors in the nation. With the 'nation level' accounting method, the sectors' embodied carbon transmission amount can be accounted for in all sectors. Previous studies have attempted to solve this issue using a one-layer network model with statistical indexes and topological indexes [26, 28-37]. However, these models and methods cannot quite detect the embodied carbon contribution of one industry to the nation when we take the level to the global level.

To solve this problem, we propose a calculable global embodied carbon transmission NoN (network of networks) model and an accounting process of sectors' contribution of embodied carbon transmission, which is shown in Fig. 1. At the 'global level', each nation is considered in its entirety. The embodied carbon contribution of the whole nation is also considered in its entirety. Based on this, we can calculate the embodied carbon contribution of the sectors based on their contribution to the nation. Thus, in our NoN model, sectors from the same nation each form a sub-network.

To calculate the nation's contribution, each sub-network is abstracted into a node, and the embodied internation carbon relationships between two nations are abstracted into one edge. Based on the abstracted one-layer nations' embodied carbon network, the embodied carbon contribution of each nation can be detected and allocated to sectors. This 'abstracting-allocating' process can detect sectors' embodied carbon contribution to their nations using global input-output tables, which is defined as a nation-based embodied carbon contribution in our research. The detailed mathematical approach is provided in the methods section.



Method	Sector A	Sector B	Sector C	Sector D	Sector E
Direct carbon emission	C_A	C_B	C_C	C_D	C_E
Embodied carbon transmission	Export $T_{A\to C}$	Export $T_{B\to C}$	Receive $T_{A\to C} + T_{B\to C}$ Export $T_{C\to D} + T_{C\to E}$	Receive $T_{C\to D}$	Receive $T_{C\to E}$
Embodied carbon transmission network	Sectors also receive or export embodied carbon from other industrial chain.				
Embodied carbon transmission NoN	Sectors contributes embodied carbon transmission contribution to their nations in different way.				

Fig 1. The example of the three level of accounting sectors' carbon emission contribution. Industrial chain level: accounting sectors' direct carbon emission amount; accounting sectors' embodied transmission amount. Nation level: accounting sectors' embodied carbon transmission amount from all sectors in the nation. Global level: accounting sectors' embodied carbon transmission amount.

Our network model and accounting method are applied in detecting sectors' nation-based embodied carbon contribution based on nation-based embodied carbon receiving and nation-based embodied carbon exporting. The results not only suggest the realizability and computability of our model and method but also lead to many interesting conclusions regarding the sectors' embodied carbon transmission. Our model and method take the sectors' embodied carbon transmission to the global level and can also be used in other fields, such as in the international trading market.

II. METHOD

A. Data avalability

The input-output tables and direct carbon emissions data were collected from 'the Eora global supply chain database'. The database contains 18 years of input-output table data and direct carbon emissions data from 1998 to 2015. Each year, the input-output table and direct carbon emissions data contain 189 nations, and each nation contains 26 sectors.

The mathematical approach of our calculating process includes 3 steps: constructing a global embodied carbon NoN model; detecting the carbon transmission contribution of each nation; and allocating nations' embodied carbon contributions to each nation's sectors. The detailed expression of each step will be provided in the following sections.

B. Constructing global embodied carbon NoN (network of networks) model.

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The calculation process of embodied carbon transmission is based on the method proposed by Ref [35]. For sector *i* in region *k*, the balance formula of carbon emissions is shown as follows:

$$dc_i^k + \sum_{n}^{j=1}\sum_{m}^{l=1} e_l^j y_{il}^{kj} = e_i^k \left(\sum_{n}^{j=1}\sum_{m}^{l=1} ip_{li}^{jk} + \sum_{n}^{j=1} f_i^{kj} \right) \quad (1)$$

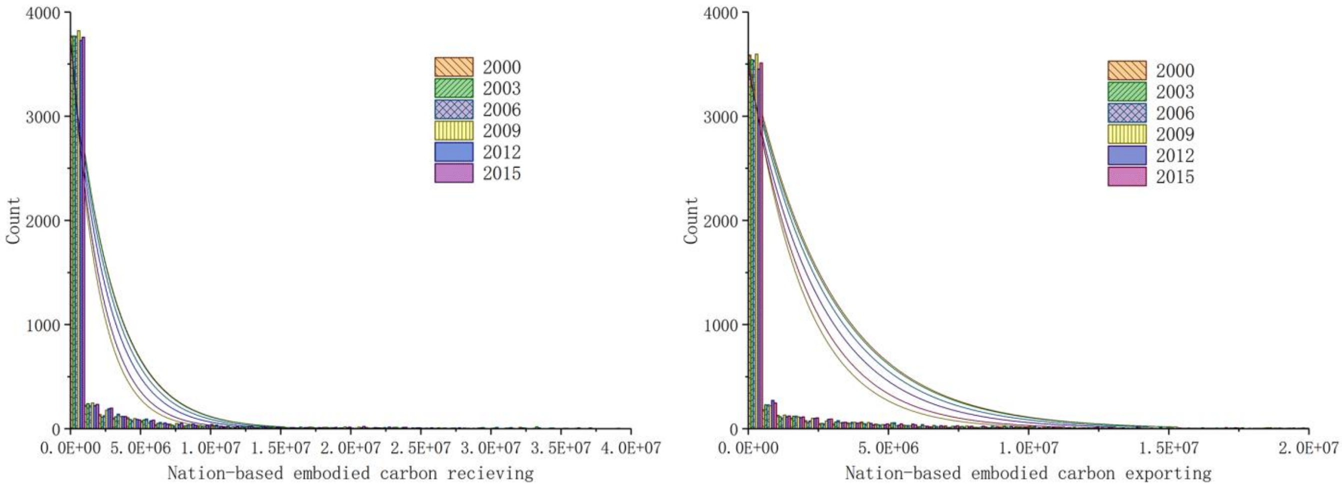

Fig 2. The distribution of 6 kinds of nation-based carbon transmitting capabilities in all global sectors.

where e_i^k represents the embodied carbon transmission strength of sector i in nation k, n is the number of nations, and m is the number of sectors in one nation. The left side of the equal sign indicates the imported carbon emissions, which contain the direct imported carbon emissions dc_i^k and embodied imported carbon emissions $\sum_{n}^{j=1}\sum_{m}^{l=1} e_l^j y_{il}^{kj}$ through purchasing other sectors' products and services. The right side of the equal sign indicates the output carbon emissions calculated by $e_i^k\left(\sum_{n}^{j=1}\sum_{m}^{l=1} y_{li}^{jk} + \sum_{n}^{j=1} f_i^{kj}\right)$.

Based on the balance formula of carbon emissions, the balance matrix formula of carbon emissions is shown as follows:

$$\boldsymbol{DC}^T + \boldsymbol{Y}^T * \boldsymbol{E}^T = \boldsymbol{F} * \boldsymbol{E}^T \tag{2}$$

where $\boldsymbol{DC}^T$ represents the transposed matrix of the direct carbon emissions matrix; $\boldsymbol{E}^T$ represents the transposed matrix of the embodied carbon transmission matrix; $\boldsymbol{Y}^T$ represents the transposed matrix of the intermediate input matrix; and $\boldsymbol{F}$ represents the transposed matrix of the diagonal matrix that contains the final demand and the intermediate output. Based on the balance matrix formula, the embodied carbon matrix can be calculated as follows:

$$\boldsymbol{E} = \boldsymbol{DC} * \left(\boldsymbol{F} - \boldsymbol{Y}\right)^{-1} \tag{3}$$

Based on the embodied carbon matrix, the global embodied carbon network of network can be constructed as follows:

$$\boldsymbol{EC} = \begin{pmatrix} \begin{matrix} e_{1;1}^{C1} & \cdots & e_{1;26}^{C1} \\ \vdots & \ddots & \vdots \\ e_{26;1}^{C1} & \cdots & e_{26;26}^{C1} \end{matrix} & \cdots & \boldsymbol{E}_{1\to 189} \\ \vdots & \ddots & \vdots \\ \boldsymbol{E}_{189\to 1} & \cdots & \begin{matrix} e_{1;1}^{C189} & \cdots & e_{1;26}^{C189} \\ \vdots & \ddots & \vdots \\ e_{26;1}^{C189} & \cdots & e_{26;26}^{C189} \end{matrix} \end{pmatrix}, \tag{4}$$

where EC represents the global embodied carbon matrix, $\begin{matrix} e_{1;1}^{C1} & \cdots & e_{1;26}^{C1} \\ \vdots & \ddots & \vdots \\ e_{26;1}^{C1} & \cdots & e_{26;26}^{C1} \end{matrix}$ represents the national embodied carbon matrix of nation No. 1, which is Afghanistan; $e_{i;j}^{Ck}$ represents the embodied carbon transmission amount from sector i to sector j in nation No. k; and $\boldsymbol{E}_{1\to 2}$ represents the internation embodied carbon relationships matrix from nation No. 1 to nation No. 2, which is from Afghanistan to Albania. Based on our idea, we abstract the nation into one node, and the internation embodied carbon transmission relationship matrices are abstracted as the weight of the edges in the global embodied carbon NoN. The weight of the edges in the global embodied carbon NoN is the embodied carbon transmission amount between the two nations. Thus, we sum all of the internation embodied carbon transmission amount as the weight, which is described as follows:

$$w_{i\to j} = \sum \boldsymbol{E}_{i\to j} \tag{5}$$

Based on this, the matrix of global embodied carbon transmission NoN can be described as follows:

Table 1. The top five highest nations and the top five highest sectors for the nation-based embodied carbon receiving amount (nation-based in-strength) and the nation-based embodied carbon exporting amount (nation-based out-strength).

Nation-based embodied carbon receiving amount												
Rank	2000		2003		2006		2009		2012		2015	
No. 1	USA	PH	Germany	PH	Germany	EHO	Germany	EHO	Germany	EHO	Germany	EHO
No. 2	Germany	PA	USA	EHO	USA	PH	USA	PH	USA	PH	USA	PH
No. 3	UK	MR	UK	HOR	UK	HOR	China	PA	China	MR	China	PA
No. 4	France	MP	France	PA	France	PA	UK	MP	UK	MP	UK	MP
No. 5	Canada	RTR	Canada	MR	Canada	MR	France	MR	France	PA	France	MR
Nation-based embodied carbon exporting amount												
Rank	2000		2003		2006		2009		2012		2015	
No. 1	USA	PH	Germany	PH	Germany	EHO	Germany	EHO	Germany	EHO	Germany	EHO
No. 2	Germany	PA	USA	EHO	USA	PH	USA	PH	USA	PH	USA	PH
No. 3	UK	MR	UK	HOR	UK	HOR	China	PA	China	MR	China	PA
No. 4	France	MP	France	PA	France	PA	UK	MP	UK	MP	UK	MP
No. 5	Canada	RTR	Canada	MR	Canada	MR	France	MR	France	PA	France	MR

Table 2. Abbreviations and full names of sectors in Table 1.

EHO	Education, Health and Other Services	PH	Private Households
HOR	Hotels and Restaurants	RTR	Retail Trade
MP	Metal Products	TRA	Transport
MR	Maintenance and Repair	TRE	Transport Equipment
PA	Public Administration	WP	Wood and Paper

$$\boldsymbol{EC}_{NoN} = \begin{pmatrix} 0 & w_{1\to 2} & \cdots & w_{1\to 189} \\ w_{2\to 1} & 0 & & \\ \vdots & & \ddots & \vdots \\ & & 0 & w_{188\to 189} \\ w_{189\to 1} & \cdots & w_{189\to 188} & 0 \end{pmatrix}, \quad (6)$$

where $\boldsymbol{EC}_{NoN}$ represents the matrix of global embodied carbon NoN and $w_{1\to 2}$ represents the embodied carbon amount from Afghanistan to Albania, abstracted from $\boldsymbol{E}_{1\to 2}$ in formula 1. Based on the global embodied carbon NoN matrix, the carbon emissions transmission contribution of each nation can be detected.

C. *Detecting the carbon transmission contribution of each nation.*

We detect the embodied carbon transmission contribution of each nation from 2 aspects: embodied carbon receiving and embodied carbon exporting. These 2 kinds of contributions can be calculated by the following 2 indexes.

To reflect the amount of embodied carbon exporting, we choose the out-strength index:

$$OS_j = \sum w_{j\to k}, \quad (7)$$

where OS_j represents the out-strength of node j and $w_{j\to k}$ represents the weight of the edge point from node j to node k. The larger is the OS_j, the greater is the strength the nation's embodied carbon exporting.

To reflect the strength of embodied carbon receiving, we choose the in-strength index:

$$IS_j = \sum w_{h\to j}, \quad (8)$$

where IS_j represents the in-strength of node j and $w_{h\to j}$ represents the weight of the edge point from node h to node j. The larger is the IS_j, the greater is nation's j receipt of embodied carbon from other nations.

Based on these two types of embodied carbon transmission contributions of nations, we can detect the embodied carbon transmission contributions of sectors by allocating the indexes to each sector.

D. *Allocating nations' embodied carbon contributions to each nation's sector.*

To restore the missing information while abstracting the global embodied carbon tables into NoN and achieve our main goal of detecting the nation-based embodied carbon contribution of sectors, the embodied carbon contribution of nations will be allocated to each nation's sectors.

Embodied carbon receiving and embodied carbon exporting is described by the transforming scale of embodied carbon. While allocating these two indexes (out-strength and in-strength) to each nation's sectors, we need to calculate the contribution of each sector to the nation's embodied carbon transforming scale. However, not only the export-oriented sectors contribute to the outward-diffusing channels of the nation but also the supporting sectors contribute services and support to the nation. Thus, the allocation of these two indexes (out-strength and in-strength) should evaluate the dominance of each node and its neighbors. To achieve this purpose, we propose an index, SEC (self-eigenvector-centrality), which is described as follows:

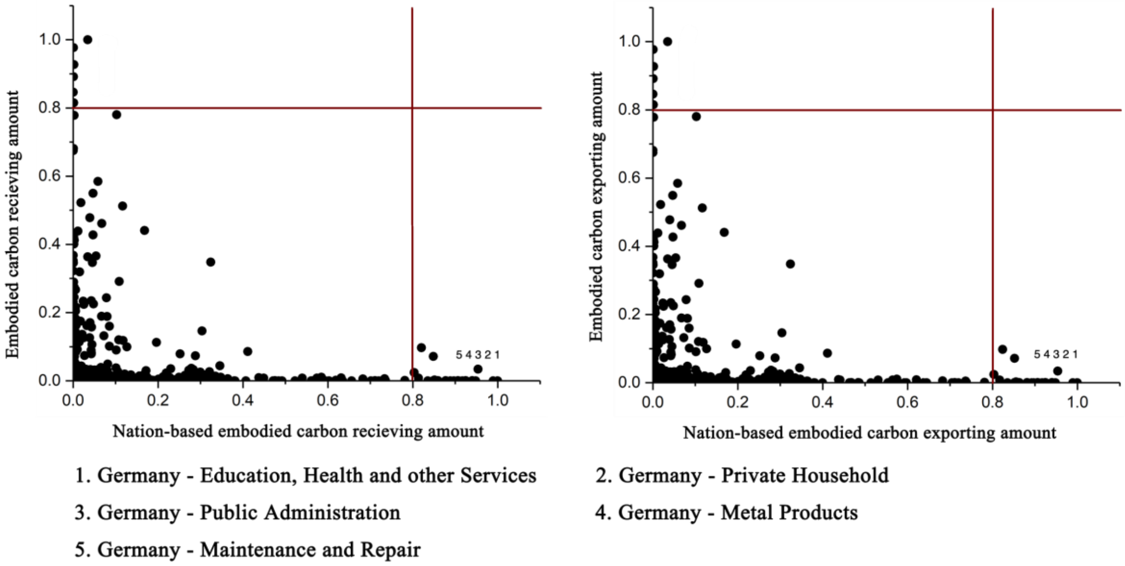

Fig 3. Comparing the nation-based embodied carbon transmitting capabilities with the carbon transmitting capabilities in 2015.

$$\boldsymbol{J}\bar{x} = \lambda \bar{x}, \tag{9}$$

$$SEC_p^{\boldsymbol{J}} = \frac{1}{\lambda} \sum_{q=1}^{m} \left(j_{pq} x_q + x_p \right), j_{pq} \in \boldsymbol{J}, \tag{10}$$

where $SEC_p^{\boldsymbol{J}}$ represents the SEC of sector p in nation J, $\bar{x}$ represents the maximum eigenvector of the network matrix, x_q and x_p belong to $\bar{x}$, and λ represents the eigenvalue of the matrix. Regarding the SEC as the evaluation index of each sector, the embodied carbon receiving and embodied carbon exporting of nations can be allocated to each sector. The A-Str (allocated strength) of each node is described as follows:

$$AOS_p^{\boldsymbol{J}} = \frac{SEC_p^{\boldsymbol{J}}}{\sum SEC_q^{\boldsymbol{J}}} \times OS_{\boldsymbol{J}}, p \in \boldsymbol{J}, q \in \boldsymbol{J}, \tag{11}$$

$$AIS_p^{\boldsymbol{J}} = \frac{SEC_p^{\boldsymbol{J}}}{\sum SEC_q^{\boldsymbol{J}}} \times IS_{\boldsymbol{J}}, p \in \boldsymbol{J}, q \in \boldsymbol{J}, \tag{12}$$

where $AOS_p^{\boldsymbol{J}}$ and $AIS_p^{\boldsymbol{J}}$ separately represent the allocated-out-strength and allocated-in-strength of sector p in nation J. Based on these two allocated indexes, the nation-based embodied carbon receiving contribution and nation-based embodied carbon exporting contribution of each sector can be calculated.

Based on the 2 allocated indexes $AOS_p^{\boldsymbol{J}}$ and $AIS_p^{\boldsymbol{J}}$ the nation-based embodied carbon receiving contribution and nation-based embodied carbon exporting contribution of each sector can be detected; the results are shown in the following results section.

III. Results

A. Distribution of nation-based embodied carbon contribution.

Based on the proposed method and indexes, the nation-based embodied carbon contribution of global sectors can be calculated. The distribution of the 2 nation-based embodied carbon indexes is shown in Fig. 2. Overall, all the distributions of the sectors' nation-based embodied carbon contributions are similar in different years. The distribution of nation-based embodied carbon indexes has a strong centrality, which means that most nation-based embodied carbon contributions focus on a small number of sectors. We further analyze the most contributory sectors, and the results are listed in Table 1.

In Table 1, we list the top five highest nations and sectors for each nation-based embodied carbon contribution. The highest nation-based embodied carbon contribution sectors all belong to developed nations, such as the U.S. , Russia and Germany, and China. There are four nations in the top five highest GDP nations on our list: U.S. , China, Germany and the UK, but not Japan. The contribution of some 'supporting sectors' (such as 'public administration', 'education' and 'health') is greater than that of the 'major sectors' (such as financial and manufacturing). In contrast to previous research, we find that the 'supporting sectors' from developed nations greatly contribute to embodied carbon transmission.

It should be noted that China does not have the highest contribution of the nation-based carbon receiving and exporting amount. Germany and the U.S. have the highest contribution of both nation-based carbon receiving amount and nation-based carbon exporting amount. This result is different from direct carbon emissions, where China contributes almost 30% of the world's total direct carbon emissions. This large difference shows that the driving factors of carbon emissions are not in China but in other industrial superdeveloped countries at the end of the production chain, such as Germany and the U.S. While

China's industrial technology is being improved to reduce direct carbon emissions, the end of the production chain needs to be improved as well. The demand-side improvements are beyond China's control; for example, the German automotive sector uses other materials instead of steel and reduces many direct carbon emissions during the production of steel.

B. Comparison results between nation-based embodied carbon transmitting capability and traditional embodied carbon transmitting capability using a one-layer network.

In this study, based on the global context, we recalculated the contribution of the sectors around the world to embodied carbon transport from a national perspective. The traditional global embodied carbon network treats the sectors as independent, reflecting the results obtained from statistical indicators. Both calculation methods have their own advantages. The nation-based embodied transmission model mainly reflects the contribution of the sector from the perspective of the whole country, including the contribution of the sector itself and the contribution of other sectors affected by the sector. For example, the embodied carbon contribution of the education sector is small, but the education sector will affect other sectors to a greater extent due to changes in the concept of carbon emissions. These mechanisms are more complex than statistical indicators. Here we only propose this concept, and more detailed mechanisms will be perfected in future research.

The comparison results are shown in Fig. 3. The results of these two calculations differ greatly, representing the difference in the contribution of the sector's embodied carbon from different perspectives. Some supporting sectors have few contributions through embodied carbon statistical methods. However, from a national perspective, their contribution is very high, even more than that of the manufacturing sectors, such as education, health, public administration, and private household. This shows that from the overall long-term perspective, we should also increase efforts to improve the understanding of carbon emissions in the supporting sectors to change the high-emissions sectors' overall impact. This is not the same as the traditional emissions reduction concept, but it may bring a better result.

IV. CONCLUSION AND DISCUSSION

With a series of devastating environmental problems caused by rising global temperatures, the reduction of carbon emissions has become one of the most important issues. The direct emissions of carbon in industrial production and the embodied flow of products are the main objects of emissions reduction. Unlike direct carbon emissions statistics, the embodied carbon flow relationship is more reflective of the incentives for carbon emissions based on demand. However, in the context of global economic integration, it is not only the contribution of one independent sector but also the contribution of other affected sectors that matters from the influence perspective. In this study, we propose an embodied carbon transmission NoN model to address the issue of embodied carbon contribution of sectors from a global perspective. Through our model, we re-evaluate the embodied carbon contribution of the global sectors and identify some of the sectors that contribute the most to embodied carbon transmission. Subsequent comparison with traditional implied carbon statistics reveals differences between the two methods.

Based on our results, we find that the sectors with the highest embodied carbon contribution are concentrated in developed countries. All the top five highest embodied carbon contribution countries are among the top six countries in terms of GDP, except for Japan. From a holistic perspective, the sectors that contribute the most are the supporting sectors such as health, education, and public administration. This is different from the traditional understanding, where these supporting sectors do not have a large amount of material flow containing embodied carbon. However, from a holistic perspective, these sectors have affected a large number of high-emissions manufacturing sectors. If we increase efforts to improve the awareness of carbon emissions in supporting sectors such as education, this will affect other sectors in a more profound way on the whole. However, the role of these supportive sectors in reducing emissions has often been ignored. Similar to the results of the comparative analysis, these high nation-based embodied carbon transmission contribution sectors are often overlooked in traditional embodied carbon statistics methods because of their low values. The results of this paper differ greatly from the results of traditional embodied carbon statistical methods, and the importance of sectors that are neglected by traditional methods is identified from other perspectives. The method in this paper can be applied to many other research fields, such as global input-output NoN and international trade NoN.

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