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China's construction industry-linked economy-resources-environment flow in international trade

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ABSTRACT

During construction, a large number of resources are consumed; concurrently, a large amount of greenhouse gas is emitted, which contributes to air pollution. There exist close interactions among construction regions. This study examined the main economy-resources-environment indexes associated with China's construction industry, embodied in international trade based on the Eora database, by using the input-output model. It investigated the linkages of the economy-resources-environment nexus and suggests recommendations accordingly. We found that the total amount of input consumption and output emissions in China's construction activities increased rapidly, both locally and abroad. China pulled much more emissions from construction-related activities abroad than the latter pulled from China. The overseas regions' dependence on China's construction industry gradually increased. Overall, China's construction activities accelerated the rate of foreign countries' resource utilization and air pollution more than it did economic profits for some of these countries. The effects on countries differed. China's construction industry was closely related to the Asian, African, and Latin American undeveloped regions. In regard to the developed regions, cooperation with Australia, the UK, Sweden and Russia was more frequent. There existed a close relationship between all the economy-resources-environment indexes. Based on the findings, protective measures were suggested, including avoiding unnecessary construction activities, optimizing China's economic and energy use structure, improving the efficient use of resources, strengthening environmental protection both abroad and locally, as well as reducing the export of products with high energy or resources consumption.

1. Introduction

The construction industry is crucial for national economic and social development as it provides essential infrastructure and buildings for human activities (Huang et al., 2018). However, it causes many environmental problems, such as natural resource depletion, greenhouse gas emissions, human-induced global warming, and air pollution (Li et al., 2017). Thus, how to address the severe effects of the construction industry has become one of the major concerns in sustainability (Lu et al., 2016). Construction not only significantly changes the landscape in the form of built-up land expansion and ecological land shrink (Chuai et al., 2015) but also releases large quantities of contaminants. Previous studies show that the construction industry is the second largest generator of carbon, contributing approximately 33% globally (Zhang et al., 2013). It consumes 25% of global water and a large quantity of raw materials, such as sand, timber, gravel, steel, cement, and plastic, and consequently produces a large amount of solid waste (Chuai et al., 2015). Production using these materials causes significant energy consumption and high amounts of carbon emissions, along with other gases such as nitrides, sulfides, and fine particulate matter (PM) (Chang et al., 2010; Huang and Bohne, 2012). Previous studies show that the construction sector consumes 40% of the total energy and releases 33% of the total carbon globally (Chau et al., 2015). This industry produces both direct and indirect emissions. Direct emissions include carbon emissions and other air pollutants from on-site construction activities (Onat et al., 2014). Indirect emissions occur in the upstream activities of industries that produce raw materials or other construction material (Kokoni and Skea, 2014; Chuai et al., 2015). In previous studies, the

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embodied energy consumption and environmental emissions usually focused on a case building at local scale, the different phrases in building life cycle are considered (Gustavsson et al., 2010; Han et al., 2013). And to reflect the relations between environmental emissions and economic development among sectors, the input-output analysis can be used, while, it is hard to conduct a comprehensively integrated assessment of special products within an economic sector at the micro scale (Li et al., 2019c). Comprehensively considering the pros and cons of the two commonly used methods, a hybrid method combining the process analysis and input-output analysis was proposed and used (Han et al., 2014, 2016; Shao et al., 2014), and Li et al. (2019c) further developed this method and quantified the embodied energy consumption and greenhouse gas emissions driven by the infrastructure engineering of case buildings in Beijing at urban, national, and global scales, respectively. The above-mentioned studies can provide methodology guidance for construction and associated environment impact analysis at micro scale.

For the macro construction industry analysis, in addition to the close interactions between the construction industry and other industries, construction regions and countries are also closely related. In the monetary flow among these regions, the consumption of resources is embodied in domestic and international trade, and hence, environmental problems such as gas emissions occur (Wiedmann and Lenzen, 2018). Multiregional input-output (MRIO) models have been developed to examine the economy and industry products and to perform environmental assessment (Nagashima et al., 2017; Zhang et al., 2018). Trade is associated with both environmental and social footprints. Previous studies show that between 10% and 70% of the global environmental or social impacts are embodied in the international trade of goods and services, for example, 24–68% of global raw material extraction, 62–64% of global metal ore extraction, 21–37% of global land use, and 23–30% of the global greenhouse gas emissions (Wiedmann and Lenzen, 2018). Based on the MRIO models, previous studies mainly focus on footprints embodied in trade, such as carbon emissions (Lenzen et al., 2018; Meng et al., 2018), food (Chaudhary et al., 2018), metal (Burke, 2018), land and biodiversity (Lenzen et al., 2012), and $PM_{2.5}$ (Guan et al., 2014). Multi-footprints have also been explored, with most studies mainly emphasizing air pollution indexes (Zhao et al., 2015, 2016; Nagashima et al., 2017); these studies have also linked land and water at the global scale (Chen et al., 2018). In recent years, the nexus of multi-footprints has become a debated topic, with various methods and models being used to link the relationship between different footprints (Perrone and Hornberger, 2016; Zimmerman et al., 2016). Studies have analyzed the water-land-energy-food nexus in agriculture (Albrecht et al., 2018; Li et al., 2019a,b); however, nexus studies in other fields, especially in the construction sector, are relatively rare, and further research is urgently required. Additionally, linkage studies on nexus relationships focus more on conceptual methods, it is therefore necessary to strengthen the quantitative analysis in this field (Albrecht et al., 2018).

China is under rapid urbanization; its built-up land is expanding rapidly, as its building activities are frequent. As the pillar industry, China's construction industry plays an essential role in the Chinese economy (Shi et al., 2017); however, it consumes large quantities of resources. Consequently, people suffer serious environmental pollution, especially air pollution (Cyranoski, 2018). In addition to the domestic building activities, China has a considerably large construction business in other foreign countries; particularly, it has a large number of construction aid projects in the undeveloped African and Asian countries (Wei, 2015). Some Chinese studies have attempted to examine both direct carbon emissions and other air pollutants, from the construction industry and indirect emissions from upstream industries (Chang et al., 2010; Chuai et al., 2015). The input-output model has also been extensively used to examine carbon emissions and air pollution among inter-regions within China and globally (Lin et al., 2014; Zhang, 2017; Zhang et al., 2017). However, this model considers all economic sectors as a single unit, hence it cannot extract certain sectors for further analysis. Thus, regarding the construction sector, examinations among inter-regions and countries still constitute a gap. Related studies concentrate on the emissions the construction industry releases both directly and indirectly and their influence on the atmospheric environment. The resources the sector consumes, the degree of air pollution and the final economic profits it produces among regions are rarely discussed. During construction, monetary investments are made for the preparation of the resources used in construction first. Resources are then consumed during the construction process. As a result, gas emissions are released. However, research on the construction's life cycle and linkage analysis of the construction-related economy-resources-environment nexus also constitute a gap.

This study fills the research gaps discussed above, by assessing the construction's process life cycle, and quantifying the economic investments and profits associated with China's construction sector in international trade. The resource inputs include water, raw materials (biomass, construction materials, ores, fossil fuel), and the emissions of CO_2, CO, SO_2, NO_x, NH_3, PM_{10}, NMVOC, and NCFC142b (Table 1). This study also qualitatively and quantitatively analyzes the linkage relationship of the economy-resources-environment nexus in detail. The novelties of this study include: (1) it adopts a life cycle angle to link the influence of China's construction industry to the economy, resources, and environment, (2) it is the first comprehensive examination of multi-indexes embodied in international trade and (3) it marks an attempt to analyze the complex nexus among various indexes. The study provides a reference for related scientific research on the conceptual, methodological, and content-related aspects of research. It can therefore provide helpful insight on sustainable development strategies for China's construction industry.

2. Materials and methods

2.1. Data

The dataset in this study includes monetary MRIO tables and data on water use, raw materials, energy use, CO_2 emissions, and air pollution. The monetary MRIO tables are collected from the Eora global supply chain database, in which the global economy is represented as 26 sectors, 188 economies, and 6 final demand coupled systems (https://www.worldmrio.com/). Additional data are also provided by the Eora database, while some original data are collected from other sources. The initial CO_2 emissions and air pollution data are from the Emissions Database of the Global Atmospheric Research (EDGAR) dataset (https://edgar.jrc.ec.europa.eu/archived_datasets.php#). The raw materials data are provided by the Commonwealth Scientific and Industrial Research Organization's (CSIRO) EW-MFA dataset (Wiedmann et al., 2015), which contains 36 material categories. The water use data are from the Water Footprint Network, dataset, National Water Footprint Statistics: water footprints of national production (Hoekstra and Mekonnen, 2012).

2.2. Definition of the construction industry

The construction industry refers to the survey, design and

Table 1
Lists of economy, resource and emission indexes.

ndexes-first level	Indexes-second level	Indexes-first level	Indexes-second level
Economy	Monetary values	Emissions	CO_2
Raw materials	Biomass		CO
	Construction materials		SO_2
			NO_x
	Ores		PM_{10}
Energy use	Fossil fuel		NH_3
Water use	Water		NMVOC
			NCFC142b

construction activities associated with construction engineering, as well as the repair activities on original buildings. It is one of the most important sectors in the national industrial structure. It usually includes civil engineering of building roads, bridge tunnels, pipeline engineering, etc. It also includes the construction's installation and decoration activities. This study does not consider the phases of building running and building demolition. However, the building running generates a large amount of energy consumption, which is especially meant for residential purposes.

2.3. Methods

2.3.1. Environmentally extended input-output model

Since the input-output model can well describe the economy and associated environmental indexes links among regions and industries (Peters, 2008), the environmentally extended MRIO is selected in this study to show the resource consumption and emissions in other regions caused by the consumption of a certain region's construction industry. Originally developed by Leontief in the 1930s (Leontief, 1936), the monetary balance can be expressed as follows:

$$X = (I - A)^{-1} Y = LY \tag{1}$$

where X is the vector of the total output, A is the matrix of the technical coefficients, and Y is the final demand vector. $(I\text{-}A)^{-1}$ is known as the Leontief inverse or the complete demand coefficient matrix, whose elements capture the direct and indirect effects from a unit change in the final demand.

The basic model has been extended in two directions: by the subdivision of the economy in a number of regions/countries that are connected by trade, and by the addition of supplementary environmental accounts. Based on the basic model, numerous researchers have developed and applied MRIO models covering multiple nations and regions to measure the embodied environmental impacts of international trade (Wiedmann et al., 2007; Wiedmann, 2009). The overall environmental multi-region set-up is:

$$F = ELY = EL(Y_d + Y_e - Y_i) \tag{2}$$

where E is the diagonalized matrix based on the vector of direct resource intensities (e.g. CO_2 emissions per unit of output) for each sector, and Y_d, Y_e and Y_i are the vectors of the final demand (household, government and investment), the exports and the imports, respectively. Based on the basic model, the territorial footprint of each environmental indicator (here, water use, raw materials, energy use, CO_2 emissions and main air pollution are environmental indicators) associated with production was calculated as follows (Kanemoto et al., 2011; Lenzen et al., 2012; Kanemoto et al., 2016):

$$F^{(p)s} = \sum_{ri} f_i^r \left[\sum_{tj} L_{ij}^{rt} Y_j^{ts} + \sum_{t \neq s,j} L_{ij}^{rs} Y_j^{st} - \sum_{t \neq s,j} L_{ij}^{rt} Y_j^{ts} \right] \tag{3}$$

where f is the intensity of the environmental indicators; L is the Leontief inverse; Y is the final demand; i and j are the sectors of origin and destination, respectively; r and s are exporting and importing nations, respectively; and t is the final destination. For instance, Y_j^{st} is a vector indicating final demand of sector j in region s that are exported to region t. Based on Equation (3), the environmental flows of the nations embodied in exports and imports can be expressed as follows (Kander et al., 2015; Steininger et al., 2018):

$$EX^s = \sum_{ri} f_i^r \sum_{t \neq s,j} L_{ij}^{rs} Y_j^{st} \tag{4}$$

$$IM^s = \sum_{ri} f_i^r \sum_{t \neq s,j} L_{ij}^{rt} Y_j^{ts} \tag{5}$$

Here, the environmental flows of different indicators in the construction sector of the nation embodied in exports and imports can be expressed as follows:

$$EX_{con}^s = \sum_{i=con,r} f_i^r \sum_{t \neq s,i=con,j} L_{ij}^{rs} Y_j^{st} \tag{6}$$

$$IM_{con}^s = \sum_{i=con,r} f_i^r \sum_{t \neq s,i=con,j} L_{ij}^{rt} Y_j^{ts} \tag{7}$$

2.3.2. Analysis of the change in indexes

Regarding the analysis of change in the economy-resources-emissions growth over time, the means of the percentage change and range of the rate of change were adopted. The detailed calculation equation is shown below:

$$Y_{mean} = \frac{\sum_{i=1}^{n} V_i}{n} \tag{8}$$

$$V_i = \frac{Q_i - Q_{i-pre}}{Q_i} \tag{9}$$

Y_{mean} is the mean of the percentage change among different time points. V_i is the rate of change of the imported or exported amount of certain indexes between time point i and its previous time point. Q_i is the imported or exported amount of certain indexes at time point i. Q_{i-pre} is the imported or exported amount of certain indexes at the time point prior to time point i. n is the number of time points.

$$Y_{range} = Max(V_i.....V_n) - Min(V_i.....V_n) \quad (10)$$

Y_{range} is the range of the rate of change among different time series. $Max(V_i.....V_n)$ and $Min(V_i.....V_n)$ indicates the maximum and minimum rates of change between time points i and n, respectively.

In order to analyze the linkage of the economy, resources, and emissions during construction's life cycle process, intersecting qualitative and quantitative methods are used together. A flow chart was drawn to show the linkage among different indexes. A correlation analysis was performed to quantitatively evaluate the relationship between the indexes. Additionally, according to the results of the correlation analysis, linear regression equations between different indexes were established according to the flow chart. The correlation and linear regression analyses were performed using the Statistical Package for Social Sciences (SPSS) software.

2.4. Other analysis

This study analyzed the total economy-resources-environment flow changes abroad associated with China's construction industry. From 1990 to 2015, time points were selected at a 5-year interval. In addition to the economic links, the import indexes abroad associated with China's construction industry include raw materials, energy use, and water use, as well as greenhouse gas emissions among other forms of air pollution caused by the industry. Overseas' export mainly caused an increase in water use and gas emissions in China (Table 2); however, the amounts of the other indexes, as in imports, were very low, hence they were excluded from the statistical frame.

The temporal variation's analysis was employed among the main world regions. According to the amount of the different indexes embodied in the import and export in international trade, only regions with indexes higher than specific values in 2015 were chosen, indicating that these regions had more important impacts. Regarding the import-linked indexes, the selected regions had an economic value higher than 1 × 10^6 USD, raw material amount higher than 1 × 10^6 t, and values higher than 1 × 10^4 t, 100 Mm^3, 1 × 10^5 t and 1 × 10^4 t for fossil fuel, water use, CO_2 and air pollution, respectively. Regarding the export-linked indexes, the economic value was higher than 1 × 10^5 USD, while the cutoff values were 1 Mm^3, 1 × 10^4 t and 1 × 10^3 t for water use, CO_2 and air pollution, respectively.

3. Results

3.1. The total amount changes of economy-resources-environment indexes associated with China's construction

The economic indexes for both the imports and exports increased. The rate of increase was especially high for imports, which increased from 1.96 billion to 135.64 billion USD. In addition, the economic investments abroad associated with China's construction industry were all significantly higher than the exports, being 2.72 times higher in 1990 and increasing to 7.66 times higher in 2015. Following frequent building activities, more building materials were consumed, and some of them were imported from abroad. The imported biomass increased from 80.65 × 10^4 t to 2778.41 × 10^4 t between 1990 and 2015. The percentage of the imported biomass accounting for the total biomass consumption, also gradually increased, from 0.85% in 1990 to 8.2% in 2015.

Similarly, construction materials also increased, with the percentage rising from 1.83% to 8.37%. Its import gradually increased 42 times from 1990 to 2015. The rate of increase of imported ores were low, rising from 31.47 × 10^4 t to 2778.41 × 10^4 t. However, imported ores accounted for higher proportions in the total ore consumption than the former two, increasing from 2.96% to 12.87% between 1990 and 2015. Energy is also essential in building activities. The amount of imported fossil fuel increased from 40.92 × 10^4 t to 1914.2 × 10^4 t. The foreign countries' energy dependence in imported fossil fuel is similar to but slightly lower than that in the ores. Regarding water use, the amount of imported

Table 2
The import and export resources-environment-economy indexes associated with China's construction industry.

Imports	Indexes	Units	1990	1995	2000	2005	2010	2015
Economy	Economy	Billion USD	1.96	8.40	15.41	37.28	103.71	135.64
Raw materials	Biomass	10^4 t	80.65	364.87	1112.42	1459.43	2392.42	2778.41
	Construction materials	10^4 t	151.78	770.53	1406.65	809.15	5185.54	6443.80
	Ores	10^4 t	31.47	152.73	299.06	442.68	768.28	945.05
Energy use	Fossil fuel	10^4 t	40.92	211.13	454.48	809.15	1482.09	1914.20
Water use	Water use	Mm^3	827.34	3730.27	7508.97	15,325.24	43,949.66	107,110.92
Emissions	CO_2	10^4 t	60.43	260.50	514.02	834.15	1369.55	1645.30
	CO	10^4 t	5.91	24.20	52.52	84.82	135.83	166.42
	SO_2	10^4 t	0.94	4.46	8.77	13.51	22.21	25.12
	NOx	10^4 t	0.60	2.30	4.64	7.02	11.08	13.04
	PM_{10}	10^4 t	0.87	3.48	7.40	11.44	18.05	21.98
	NH_3	10^4 t	0.57	2.08	4.88	6.80	10.51	12.24
	NMVOC	10^4 t	1.43	3.89	8.78	12.81	20.31	24.49
	NCFC142b	10^4 t	0.66	2.15	4.19	6.06	9.36	10.54
Exports	**Indexes**	**Units**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**
Economy	Economy	Billion USD	0.76	2.35	3.36	8.12	18.38	18.11
Water use	Water use	Mm^3	2.45	7.55	10.57	26.22	59.20	58.29
Emissions	CO_2	10^4 t	112.27	263.29	194.32	323.01	317.50	251.57
	CO	10^4 t	1.782	3.946	2.098	3.292	3.232	2.162
	SO_2	10^4 t	1.043	2.193	1.161	1.892	1.827	1.222
	NOx	10^4 t	0.344	0.782	0.467	0.798	0.768	0.514
	PM_{10}	10^4 t	0.155	0.319	0.162	0.245	0.220	0.147
	NH_3	10^4 t	0.006	0.008	0.007	0.009	0.007	0.005
	NMVOC	10^4 t	0.045	0.068	0.035	0.066	0.061	0.041
	NCFC142b	10^4 t	0.012	0.015	0.013	0.017	0.014	0.009

water increased from 827.34 Mm^3 to 107,110.92 Mm^3—the highest increase compared with the other indexes. Imported water accounted for the highest proportion in the total water, increasing from 4.7% in 1990 to 18.02% in 2015. However, the amount of water use embodied in international export trade was significantly lower than that embodied in import trade. During the building process, gases were also emitted. As shown in Table 2, the amount of gas emitted pulled by the imports were all significantly higher than those of the exports, and the rate of increase of emissions pulled by imports was also more evident than the rate for the exported emissions. Moreover, the percentages of some emissions pulled by imports, accounting for total individual emissions, were high; for example, the percentage of NCFC142b reached 55.85%, while those of the PM_{10}, CO, and NMVOC were 19%%, 16.95%, and 16.12%, respectively. Temporally, the period from 2000 through 2010, especially from 2005, showed an increase for most indexes. However, the rate of increase slowed down between 2010 and 2015.

3.2. The distribution of index amounts among world regions in international trade

This study shows the differences in the spatial distribution among the world regions in 2015. Raw materials are the sum of biomass, construction materials and ores, while air pollution is the total amount of gas emissions except CO_2 as shown in Table 2. Regarding imports, the differences in the spatial distribution are shown in Fig. 1. Economic investments abroad associated with China's construction industry show adequate distribution among the continents. For example, Portugal, Russia, France and the UK in Europe, Jamaica and Canada in North America, Sudan and South Africa in Africa, and Israel, Singapore, and India in Asia all have high values. Australia had the 17th highest value, with 233 $\times$ 10^4 USD. However, the link to the United State of American (USA) was relatively low, with only 1.5 $\times$ 10^4 USD. Regarding the use of raw materials abroad, undeveloped regions, such as Africa, particularly South Africa, Sudan, and Morocco, are always important sources, with their import amount varying between 200 $\times$ 10^4 t and 600 $\times$ 10^4 t. Asian countries such as Israel, the Philippines and India, showed import amount ranges similar to those of the above named African countries. In Latin America, El Salvador had the highest value among all the regions, at 1261 $\times$ 10^4 t. Trinidad and Tobago and Brazil also recorded high amounts of imported raw materials, at 622 $\times$ 10^4 t and 252 $\times$ 10^4 t, respectively. In Europe, Iceland recorded the second highest value among all the regions, at 1005 $\times$ 10^4 t. However, most developed regions in Europe, such as Russia, Belgium, Denmark, and France, presented lower and similar amounts, varying between 160 $\times$ 10^4 t and 180 $\times$ 10^4 t. Australia's import amount was 126 $\times$ 10^4 t. In North America, Jamaica recorded a value of 214 $\times$ 10^4 t; however, Canada and USA recorded lower values, at 72 $\times$ 10^4 t and 20 $\times$ 10^4 t, respectively. Regarding the use of fossil fuel, many undeveloped regions recorded high values, with Uruguay and South Africa recording the highest and second highest, respectively. In Latin America, El Salvador, Trinidad and Tobago and Brazil were the 4th, 5th, and 13th highest, respectively. The regions with high fossil fuel use in Asia mainly include India, Israel, and Indonesia. Russia, Australia, and Canada also recorded high fossil fuel use. Similar to fossil fuel, the use of imported water also recorded high values in many undeveloped regions, such as Asia and Africa. In addition, similar to the input of raw materials and fossil fuel use, water use in Russia, Iceland and Canada also recorded high values. Generally, the output of CO_2 and air pollution also corresponds to the main input distribution, where high input consumption always shows high emissions.

Fig. 2 shows the variation in the distribution of export-linked indexes, indicating the goods and services provided by China's construction industry to foreign regions and countries. It shows

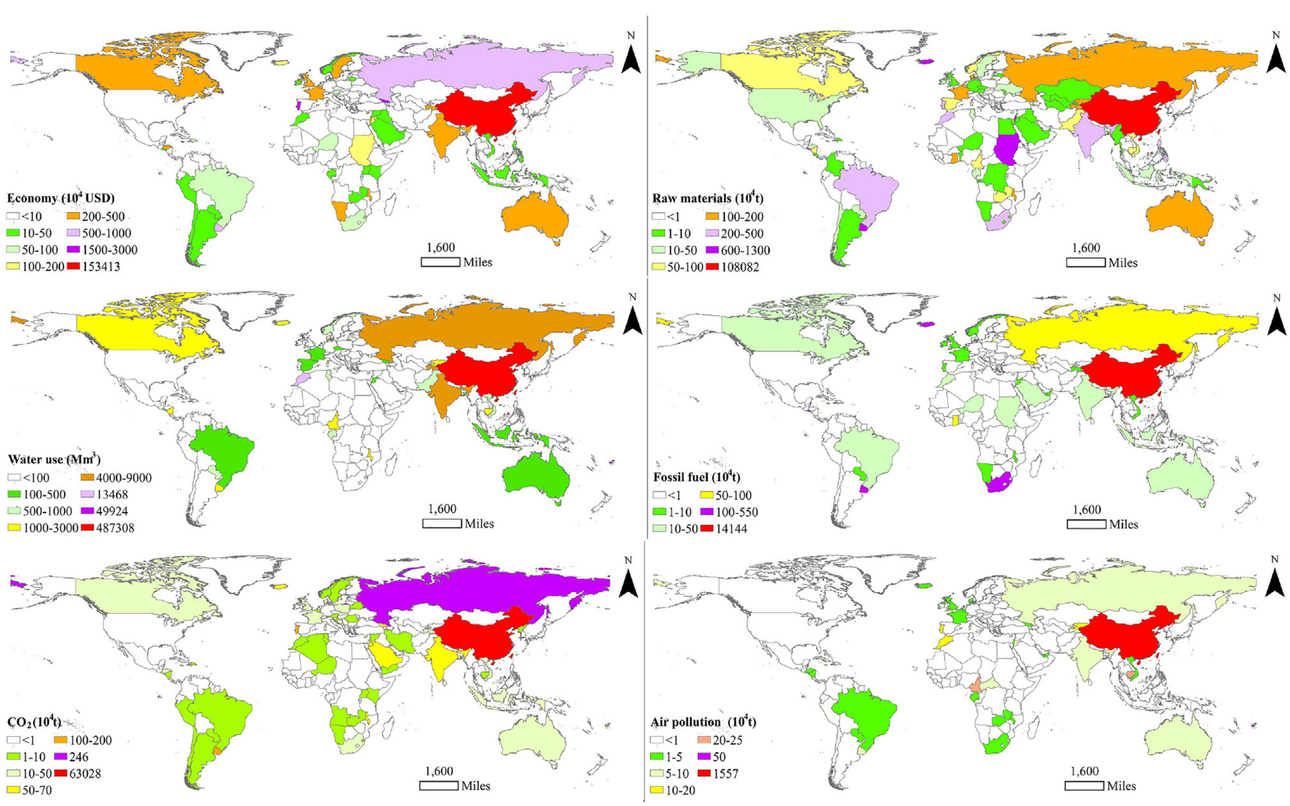

Fig. 1. Distribution of the resources-environment-economy index amounts among world regions pulled by China's construction industry in import in 2015.

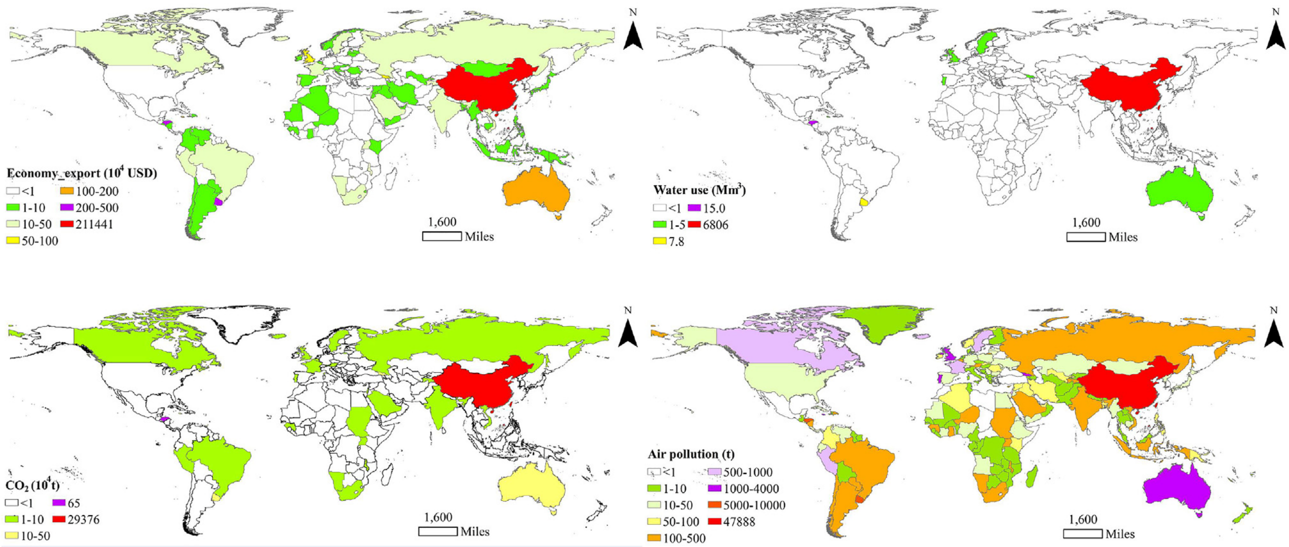

Fig. 2. Distribution of resources-environment-economy index amounts among world regions that China's construction industry was pulled in export in 2015.

that, in contrast with the import, economies abroad mainly pulled water use, CO_2, and air pollution emissions from China, but the amounts were all significantly lower than their import-linked counterparts. In regard to the other indexes, since the amounts were too low, similar to the imports, this study did not analyze them. Water use pulled by regions abroad had low values as only eight countries had amounts higher than 1 Mm^3: (from high to low) Honduras, Uruguay, Australia, Jamaica, Georgia, the UK, Portugal, and Sweden. In Latin America, Honduras and Uruguay showed the strongest effect with regard to pulling CO_2 emissions from China, with 65×10^4 t and 33×10^4 t, respectively, followed by Australia and some developed countries in Europe. Regions in Asia, Israel, Singapore, and India showed relatively high values. The amount that Canada pulled was close to that of Israel. The export-linked economy corresponded well regarding the use of water and CO_2 emissions, with the order of the top 16 regions from high to low completely the same. The use of water and CO_2 emissions presented even higher similarities, with the order of nearly all regions being the same. However, regarding air pollution, the emissions amounts all showed low values. Only Honduras had air pollution values higher than 1×10^4 t. Regarding emissions, the order of the highest values also corresponds to that of the other indexes, with the top 16 regions being completely the same to the others.

3.3. Temporal variation in the index amounts among main world regions

Fig. 3 shows the import-linked indexes. It shows that all indexes showed increasing trends between 1990 and 2015. The mean percentage change and range of change correspond efficiently to each other. Regarding China, all indexes showed a relatively low mean percentage increase and a narrow range of change. High increase rates occurred more frequently in undeveloped regions. The raw materials, fossil fuel, and air pollution had higher values than all the other indexes. In regard to the economy, the mean percentage increase and rate of change of the selected regions varied between 109%-269% and 134%–822%, respectively. Malawi, Jordan, Iceland, Singapore, Portugal, Sweden, Tajikistan, India, and Sudan showed a wide range of changes and rates of increase higher than 200%. Raw materials showed a significantly wider range of variation of 59%–2174% for the mean percentage change and 192%–10782% for the range of change. Portugal recorded the highest rate of increase, followed by Sudan, Israel, and Russia, all of which had a mean rate of increase higher than 1000%. The period from 2000 through 2005 is the only time several regions showed a decreasing trend. The mean percentage increase and range of change of fossil fuels use correspond to those of the raw materials; Indonesia recorded the highest values, at 2780% and 13,437%, respectively. The mean percentage increase dropped, with Niger being the second highest at 788%, followed by Ghana, El Salvador, Trinidad and Tobago, Viet Nam, and Paraguay, all with a percentage increase of approximately 500%. The mean rate of increase of water use showed moderate values compared with the other indexes; the mean percentage increase varied between 97% and 537%; therefore, only El Salvador, Tunisia, and Cambodia had values higher than 500%, with their range of change being approximately 2000%. Regarding the emissions, the change in CO_2 emissions was slightly lower than that of water use, which was higher than 300% in El Salvador and Indonesia. Regarding air pollution, Russia is the only region that recorded a high mean increase of 1819%. Fiji, Jordan, and El Salvador, however, dropped significantly to 623%, 603%, and 535%, respectively.

Compared with the imports, the mean rate of increase and range of change for all the export-linked indexes were significantly low, showing a mean rate of increase of 89%–217%, 89%–140%, 20%–107% and 9%–41% for the economy, water use, CO_2 emissions and air pollution, respectively. Similar to Iceland, a higher increase in the economy occurred more in the undeveloped regions, such as Viet Nam, Tajikistan, India and Singapore in Asia, Peru, Brazil, Trinidad and Tobago in Latin America, and Uganda, Malawi, and Mauritius in Africa. Regarding the CO_2 emissions, the order of regions from high to low based on the mean rate of increase corresponded efficiently to the economy. The regional differences in water use and air pollution showed a similar order, with Portugal and Honduras recording the highest and the second highest values, respectively (Fig. 4).

3.4. Economy-resources-environment nexus analysis

Following the frequent economic and social activities embodied in international trade, China's construction industry has close economy-resources-environment linkages within China as well as

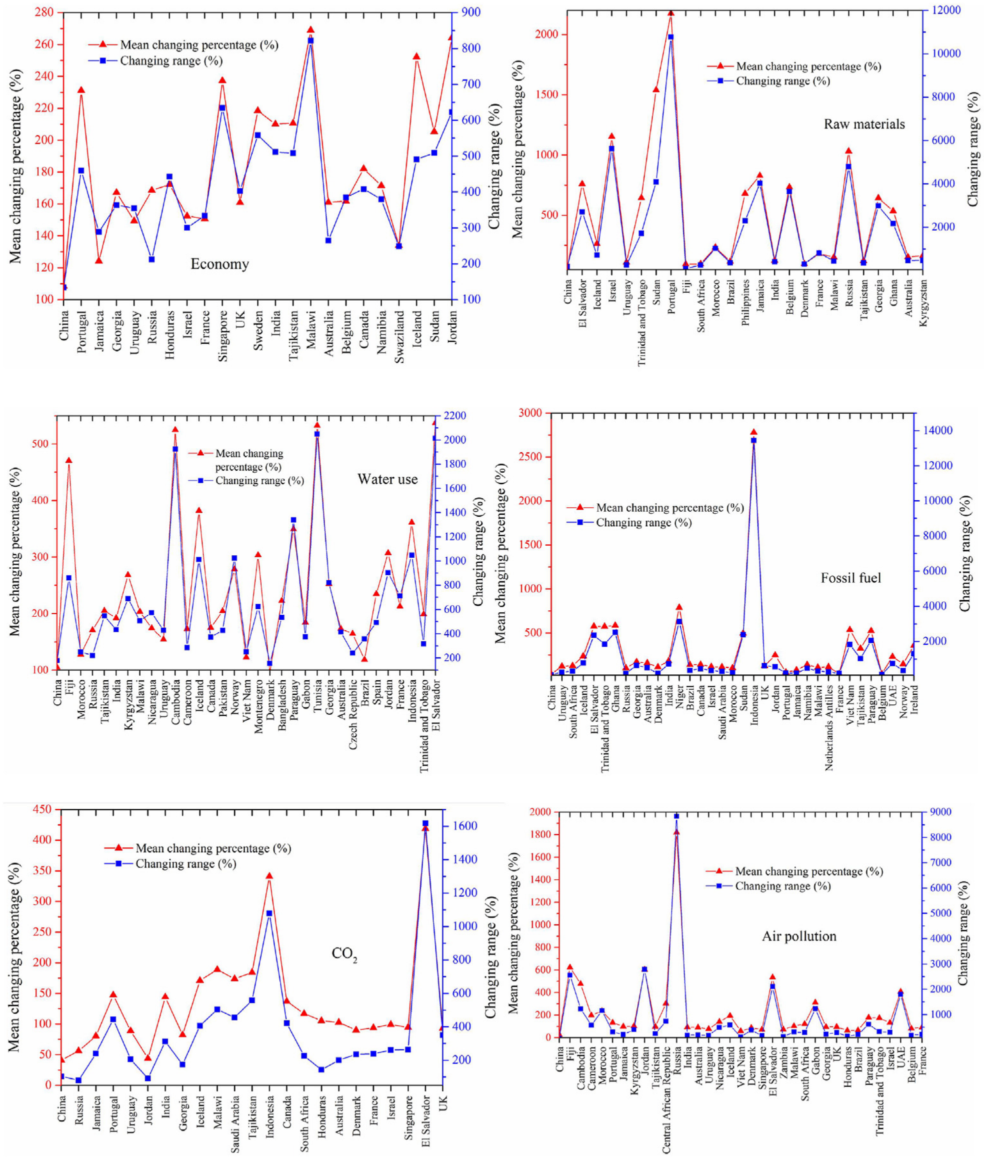

Fig. 3. Mean changing percentage and changing range of the import-linked indexes for the main world regions between 1990 and 2015, with time intervals of 5 years. The regions in the abscissa are listed by their index absolute amounts from high to low from left to right.

with international regions. The linkage is shown qualitatively in Fig. 5. Through economic investments, inputs such as raw materials, water, and fossil fuel are consumed during construction, and water and raw material use promotes energy use. During the input index consumption process, especially for fossil fuel, greenhouse gases, along with other air pollutants, are generated and released into the atmosphere. The import values indicate the pull effect from China to regions abroad, and the export values indicate the pull effect from regions abroad to China. The amounts of the import-linked indexes are significantly higher than the amounts of the export-linked indexes. Thus, the statistics in the above analysis include all indexes shown in Fig. 5 but omit raw materials and fossil fuel use for export.

Quantitatively, a correlation analysis was conducted to analyze the linkages among different indexes. As shown in Table 3, the import-linked indexes' correlation coefficients recorded high values of 0.993–1, which were all significant at the $P < 0.01$ level. The correlation coefficients between the export-linked indexes recorded even higher values, all of which were close to 1. The high coefficients indicate that the economy, resources, and the environment are all tightly linked.

Linear regression models were established to conduct further quantitative analysis. The model construction strictly followed the linkages in Fig. 5, especially for imports. In regard to exports, since some of the indexes had very low amounts based on the above calculation, the economy was used as an independent variable (X) to analyze the pull effect on water use, CO_2 emissions, and air pollution. As shown in Table 4, all the models showed a high fitting accuracy, with all R^2 values higher than 0.99. Moreover, all the models were significant at the $P < 0.01$ level. These linear regression equations can also provide basic mathematical support to better describe the relationship between indexes, as shown in Fig. 5, and to establish complex system models (such as the system dynamics model) to better analyze their linkages, especially for prediction analysis.

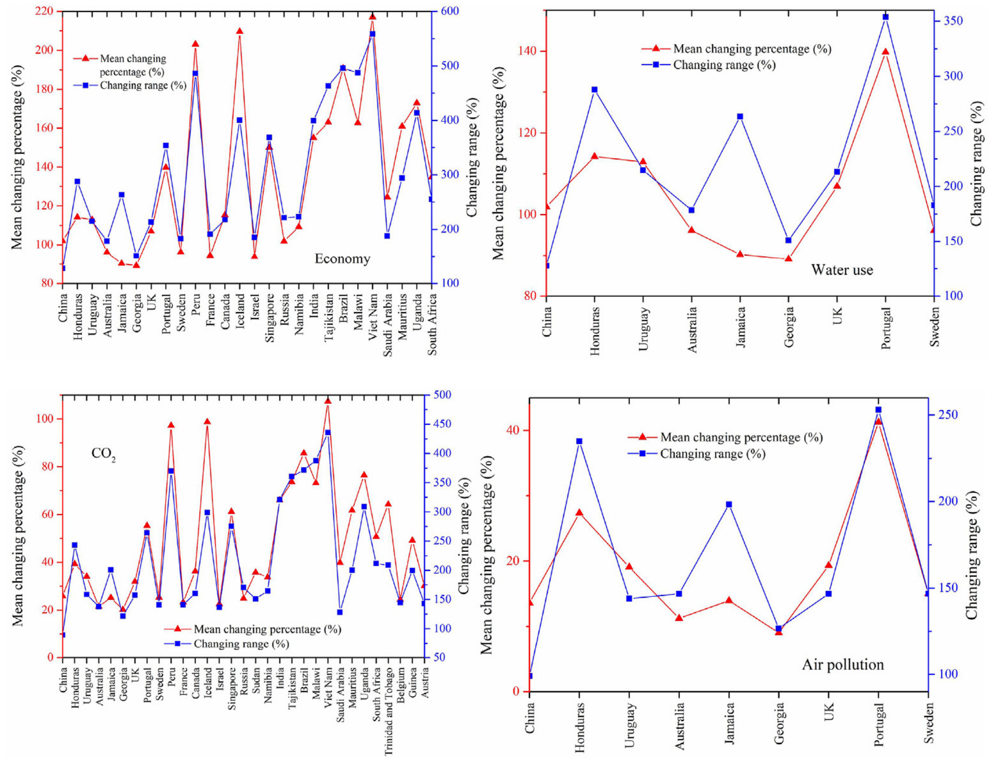

Fig. 4. Mean changing percentage and changing range of the export-linked indexes for main world regions between 1990 and 2015, with time intervals of every 5 years. The regions in the abscissa are listed by their index absolute amounts from high to low from left to right.

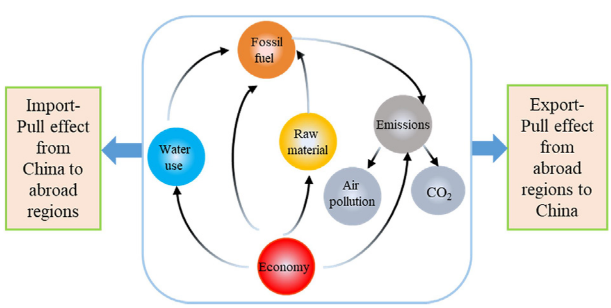

Fig. 5. Flow chart and the nexus exhibition of Economy-Resources-Environment indexes.

4. Discussion

During urbanization, the construction industry within China developed rapidly, which pulls considerable resource consumption from world regions and generates considerable amounts of greenhouse gas emissions among other forms of air pollution. Foreign countries also pull construction activities from China by using goods and services from their construction industry. Based on the perspective of the life cycle, this study examined indexes of the economy, resources and the environment embodied in international trade and analyzed the nexus among different indexes. This study is important as it fills research gaps. The main findings can help to diagnose the flow characteristics among world regions and sustain the construction industry's development based on the problems found in the analyzed results.

The economy, resources, and emissions flow in the life cycle of the construction process. However, this study differs from other life cycle studies. We did not consider the phases of building use and demolition. Furthermore, construction can pull large amounts of indirect energy from upstream industries, with the amounts being significantly higher than those directly caused (Chuai et al., 2015; Chen et al., 2017), and a considerable amount of gases can be generated (Chen and Chen, 2010; Chen and Zhang, 2010). Building materials' production consumes the largest amount of energy (Yan et al., 2010; Bin and Park, 2012), followed by the building operation stage (Cui et al., 2019). Thus, the index amounts in our calculation framework may be significantly lower if we consider other stages in the building life cycle, such as building use and demolition.

Energy-related emissions are the main air and environment polluters of the country (Chang et al., 2010). China's construction industry has undergone different stages of development. In 1953

Table 3
Correlation coefficients between import-linked indexes.

Indexes	Economy	Raw materials	Water use	Fossil fuel	CO_2	Air pollution
Economy	**1**	1**	0.994**	0.999**	1**	0.999**
Raw materials	–	**1**	0.995**	0.999**	1**	0.999**
Water use	–	–	**1**	0.993**	0.994**	0.997**
Fossil fuel	–	–	–	**1**	0.999**	0.998**
CO_2	–	–	–	–	**1**	0.999**
Air pollution	–	–	–	–	–	**1**

Table 4
Regression analysis results between indexes having linkages.

Y	X	Equation	R^2	P
Import				
Raw materials	Economy	$Y = 35{,}907 + 0.704X$	0.999	0.000
Water use	Economy	$Y = 355 + 0.0001X$	0.988	0.000
Fossil fuel	Economy	$Y = 37{,}302 + 0.092X$	0.997	0.000
CO_2	Fossil fuel	$Y = -371 + 0.004X$	0.998	0.000
Air pollution	Fossil fuel	$Y = 3.5 + 0.0001X$	0.996	0.000
CO_2	Economy	$Y = -213 + 0.0001X$	1	0.000
Air pollution	Economy	$Y = 37{,}302 + 0.0001X$	0.992	0.000
Export				
Water use	Economy	$Y = 0.003 + 3.219\ E^{-6}X$	1	0.000
CO_2	Economy	$Y = 0.145 + 0.0001X$	1	0.000
Air pollution	Economy	$Y = 0.002 + 2.265E^{-6}\ X$	1	0.000

through 1985, its total outputs gradually increased, with an annual mean rate of increase of 9.7%. China aided many developing countries and regions in construction, with the number of such regions exceeding 70 between the 1960s and the 1970s. Since the reform and opening up in 1978, China has experienced rapid urbanization and economic growth (Zhou et al., 2004). The outputs of the construction industry increased by 133 times, while its practitioners increased from 1010×10^4 to 5093×10^4 (National Bureau of Statistics, 2016). In addition, international cooperation and communication gradually became more frequent. China provides considerable infrastructure construction aid abroad, especially for undeveloped countries and regions (Hu et al., 2019). As China's industry developed, import- and export-linked indexes gradually increased from 1990 to 2015. The period from 2000 through 2010, especially from 2005, showed an increase in most indexes, which corresponds efficiently to the changing trend of the outputs of the construction industry and its practitioners provided by the National Bureau of Statistics. This is adequately determined by the urbanization process characteristics. Previous studies show that built-up land expanded the most after 2000 (Chuai et al., 2015, 2019); however, the rates of increase dropped after 2010 (Chuai et al., 2019). The percentages of indexes consumed or gases emitted from regions abroad gradually increased. This is determined by the more frequent construction activities taking place abroad (Huang et al., 2018) and the more severe external dependence on the use of resources, especially for energy imports (Roberts and Rush, 2012). The amounts of economic investment, resources and emissions embodied in imports were significantly higher than those embodied in exports, which efficiently corresponds to the actual situation. China anticipates more construction activities and imported resources for construction from abroad. In contrast with other industry sectors, such as agriculture (Chen et al., 2018), livestock breeding (Guo et al., 2019), and the heavy industry, the construction industry has no direct products, and the services it can provide to regions abroad are lower.

Regional differences show that China's construction industry is tightly linked to the undeveloped regions such as Africa, Asia and Latin America more than it is to the developed countries and regions. This is effectively determined by the fact that most developed regions, such as the USA (Kuang et al., 2014) and Europe (Salvati et al., 2018; Schulp et al., 2019), are already completely urbanized. Such regions have relatively mature infrastructure and high construction technology levels. However, their market demand for foreign participation is low. This is quite different from China's total economy and the embodied resources and emissions in international trade, which always show closer linkages with developed regions, such as the USA and some European nations (Lin et al., 2014; Kanemoto et al., 2016). Meanwhile, some of the resources used in China's domestic construction activities are imported from abroad. In addition to the pull effect from the economy, the regional natural resource endowment has an important effect on the imported amounts. For example, according to our calculation, some regions rich in iron ore, such as Australia, Brazil and South Africa (Beukes et al., 2003), are also the top regions from which China imports ores. The national foreign trade policy can also affect the actual resources trade amount; for example, Russia replaced Saudi Arabia and has become China's top oil importing country. Finally, the use of resources and emissions amounts linked to China's construction industry is comprehensively affected by the above discussed factors. The increasing trend analysis shows that high values are more concentrated in undeveloped regions, indicating that construction cooperation between China and undeveloped regions has become deeper. This is due to China's diplomacy and economic policy, such as the "One Belt and One Road" development strategies (Zhao et al., 2019) and the "South-South" cooperation (Meng et al., 2018); for example, China and Trinidad and Tobago established a close bilateral trade relationship under the "One Road and One Belt" framework. As a result, the high resource amounts of the small country are linked to China's construction industry. Another important reason is that most of these undeveloped regions are under urbanization and have more construction demand than the developed regions.

The nexus analysis shows that economic activities are the original source driving resource use directly; this finding coincides with those of studies on other nexuses, such as the water-land-energy-food nexus in agriculture (Albrecht et al., 2018; Chen et al., 2018). Thus, international trade plays a key role in the embodied use of resources, and the resulting emissions, national economic strategies, and changes in the situation of the global economy can greatly determine the resource and emissions flow in certain nexuses. For example, China's global trade's golden age after joining the WTO (World Trade Organization) was interrupted in mid-2008 when the financial upheaval initiated by the USA subprime mortgage crisis began to spread across the world (Liu et al., 2009) and caused the decline of the use of resources and gas emissions.

5. Policy implications

According to the analysis, we drew some policy implications. First, the economy development is the source power to promote construction activities, the influence to resources consumption and environment need to be seriously considered, purely pursuit of economic interests should not be encouraged, both domestic construction and foreign anticipated construction engineering need to be assessed critically in order to consider the necessity and feasibility, and avoid the unnecessary waste of resources and environment damage. Second, China's economy relies heavily on the construction industry, the industry's structure adjustment and optimization is the most important measure, and hence, the development of real economy should be strengthened. An essential level of construction engineering is undoubtedly needed. Simultaneously, unnecessary practices should be controlled, especially for the significant expansion of real estate, which has become a pillar industry in China but has also subjected China's common people to great economic pressure.

Third, except for the local construction activities, the abroad construction activities are also frequent, especially for undeveloped countries. During the construction process, the protection to local environment should be seriously, the intensive use of resources and pollution control should be highly prioritized. This is especially for region with fragile ecological environment condition, such as Africa. And, the awareness of environmental protection and environment improvement technology are relatively weak in undeveloped countries, China might help them to make up the deficiency. Fourth, according to the economy-resources-environment analysis, fossil fuel consumption directly cause greenhouse gas emissions and air pollution (Zhang et al., 2018), we suggest that China reduce the use of resources and products with high energy consumption, which will significantly reduce greenhouse gas emissions and air pollution. Although it may bring about economic loss, it is worthy as it protects the environment and human health.

Fifth, China's energy structure still heavily relies on coal, which is a relatively dirty form of energy that generates carbon and causes air pollution. Energy structure optimization is critical to environmental protection (Yu and Kong, 2017), the exploitation and utilization of clean energy such as solar power and wind should be encouraged (Chen et al., 2011a, 2011b). Additionally, green building technology (Li and Cui, 2017; Hossain, 2018) and the use of new building materials (Hong et al., 2016) must be encouraged, as both can help in saving energy and reducing gas emissions. Attention should also be paid to the efficient use of energy. The amount of energy consumption in upstream industries is significantly higher than that in the construction sector itself. The efficient use of energy in China is still very low, and therefore, must be improved (Xie et al., 2015). In conclusion, further technology learning from developed countries is required.

6. Conclusions

Following the increase in construction investments, China's construction industry grew continuously and rapidly. There exist frequent, close and bi-directional connections between China's construction industry and foreign regions. Following China's rapid urbanization and more frequent international economy cooperation, the total amount of input consumption and output emissions related to China's construction industry increased rapidly, both locally and abroad, and especially from 2000 through 2010. However, the rate of increase slowed down between 2010 and 2015.

China's construction industry has closer connections with the undeveloped regions particularly in Asia, Africa and Latin America. China pulled much more foreign construction-related activities than the foreign regions did. However, the overseas countries' dependence on China's construction industry is evident. The import-linked raw materials, fossil fuel and air pollution had higher increasing rates than other indexes did, indicating that China's construction industry accelerated the rate of foreign resource utilization and air pollution. Reversely, foreign countries and regions in international trade more pulled the increasing of China's economy than the resources consumption and emissions in China. Between 1990 and 2015, all the indexes associated with China's construction industry in international trade experienced increasing trends. High increasing values occurred more in the undeveloped regions, which means that the cooperation with the undeveloped regions became more frequent. In regard to the developed regions, cooperation with Australia, the UK, Sweden, and Russia was more frequent.

There exists a close relationship between all the economy-resources-environment indexes. Through economic investments, water and raw materials were consumed; this process promotes energy use and generates greenhouse gas and, hence, air pollution. To protect the environment, measures such as avoiding unnecessary construction activities, optimizing China's economy structure and energy use structure, improving the efficient use of resources, strengthening environment protection both abroad and locally and reducing the export of products with high energy or resources consumption must be integrated considering the economy-resources-environment nexus and international influence.

In future studies, more indexes associated with the construction industry might be collected to make a more detailed examination of the influence from construction. This study does not consider the phases of building running and building demolition, which can also generate considerable energy consumption, further studies need to include this phrase to finish a complete life cycle process for construction industry. And, analysis which not only can reveal the linkages among regions, but also include the relationship between construction industry and other industries should be explored to make a deeper analysis.

CRediT authorship contribution statement

Xiaowei Chuai: Conceptualization, Methodology, Software, Writing - original draft. **Qinli Lu:** Supervision. **Xianjin Huang:** Conceptualization. **Runyi Gao:** Data curation, Software. **Rongqin Zhao:** 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.

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