Impact of participating in global value chain on the carbon dioxide emissions of China's equipment manufacturing industry

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Impact of participating in global value chain on the carbon dioxide emissions of China's equipment manufacturing industry

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Abstract

As the pillar industry in China's post-industrial era, the equipment manufacturing industry has played an important role of providing technical equipment for downstream industries, which also brought about a substantial increase in CO_2 emissions. Therefore, in order to find ways to reduce the carbon dioxide emissions of the equipment manufacturing industry, this paper based on the global value chain production length decomposition model, improved the CO_2 emission effect model and the STIRPAT model to study the different impact of the GVC production length on the CO_2 emissions of China's equipment manufacturing industry under different GVC participation modes. The study found that extending GVC production length can effectively reduce CO_2 emissions, and the CO_2 reduction effect of the simple GVC production length is the most significant. Besides, with the extension of the GVC production length, the CO_2 emissions of high-tech industries have decreased, while the CO_2 emissions of medium-technology industries have increased. In addition, the improvements of policy regulations, factor structure and foreign investment will also reduce CO_2 emissions, but the expansion of production scale and R&D investment will increase CO_2 emissions.

Keywords Global value chain • GVC production length • CO_2 emission • Equipment manufacturing industry • CO_2 emission effect model • STIRPAT model

Introduction

In the process of China's industrialization, China's equipment manufacturing industry assumes an important function of providing equipment and technical means for downstream industries (Liu and Zhu 2019), participating in the Global Value Chain (GVC) has greatly improved the level of production technology and production efficiency, which has brought huge economic profits and technical experience returns. But at the same time, because China's equipment manufacturing industry has a low degree of participation in GVC and is a resource-consuming industry (Wang et al. 2021), it has long become a major CO_2 emitter in China (Guy et al. 2020). Since 2000, its CO_2 emissions have accounted for about 9% of China's total CO_2 emissions, and is about 10 times the level of CO_2 emissions in industrialized countries (such as the United Kingdom, Germany, etc.), which is much higher than the average level of CO_2 emissions of the global equipment manufacturing industry. Therefore, in the context of China's accelerated implementation of the "1+X" planning system of "Made in China 2025", the equipment manufacturing industry must take the "green" path of independent innovation and sustainable development to achieve the transformation of high-quality and low-CO_2 production. Hereto,

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what impact will the deepening of participation in GVC have on the CO_2 emissions of China's equipment manufacturing industry? Will the different modes of participating in GVC have different impact? What other factors also affect the CO_2 emission of China's equipment manufacturing industry? The solution of the above problems will provide strong theoretical support for China's equipment manufacturing industry to find a path of low-CO_2 development from the perspective of GVC.

To answer the above questions, the remainder of this paper is structured as follows: The "Literature review" section briefly reviews the current literature. The "Theoretical model" section presents the reasoning of the CO_2 emission effect model with the participation of the GVC. The "Methodology and data" section depicts the GVC production length decomposition model and the econometric model of STIRPAT model, and affords data sources. The "Empirical results" section analyzes the regression outcomes of panel data of the equipment manufacturing industry from 2000 to 2014. Finally, the "Conclusions and policy implications" section provides the conclusions and targeted policy suggestions.

Literature review

At present, domestic and foreign scholars have few researches on the impact of participating in GVC on the CO_2 emissions of equipment manufacturing industry. Relevant research mostly stays at the level of manufacturing industry. Besides, the measurement methods of GVC and research conclusions are also quite different. Through combing the related literature, this paper found that the measurement indicators of GVC are mainly divided into three aspects: GVC position index, GVC participation index and GVC production length. The research conclusions mainly include the following three points.

First of all, participating in GVC will increase the CO_2 emissions of equipment manufacturing industry. The reason is that the low GVC participating degree of China's manufacturing industry is harmful for energy-saving and CO_2-reduction. The expansion of low-end production activities has promoted the increase of CO_2 emissions. Based on GVC position index, although China's manufacturing industry has improved trade competitiveness and basically shows an upward trend in GVC (Wei and Zhang 2020), it is difficult for China's equipment manufacturing industry to escape the development dilemma brought by the "low-end lock-in" of GVC (Chen and Wang 2015), which have aggravated the pollution problem caused by CO_2 emissions (Sun and Du 2020), the phenomenon is particularly obvious in capital and technology-intensive industries (Wang 2014). Moreover, in terms of the GVC participation index, China's equipment manufacturing industry has a very high degree of "backward participation" in the GVC (Pan 2019), which requires more energy and resource input (Zhao et al. 2020), and makes CO_2 emissions increase (Chang et al. 2020). Meanwhile on the basis of the GVC production length, after the extension of the GVC production length and the expansion of the scale of processing trade, the CO_2 emissions generated by the manufacturing industry will also increase before the widespread application of cleaner production technologies (Zhao and Yang 2020). The low participating degree of China's manufacturing industry reflects the characteristics of weak technology (Li and Yuan 2016), poor factor structure (Lu et al. 2018), and strong mass production demand (Kang 2018; Edger 2020), which are also important factors to promote the increase of CO_2 emissions (Xie et al. 2018).

Secondly, participating in GVC will decrease the CO_2 emissions of equipment manufacturing industry. With the improvement of the GVC participation level of China's manufacturing, its technological level will continue to improve (Zhang and Gallagher 2016), and the output structure will continue to be optimized (Zhang et al. 2020). These value creation factors will enhance the impact on environmental sustainability (Stock et al. 2018), and provide a powerful boost to the energy saving and CO_2 emission reduction of China's manufacturing industry. The climb of the GVC position is conducive to reducing manufacturing CO_2 emissions (Zhang et al. 2018). Then, in the process of participating in GVC, China will improve the clean technology level of enterprises through imitation, learning and secondary innovation, urge enterprises to move upstream of GVC, and reduce environmental pollution (Cai et al. 2020). The rise of GVC participation index based on simple mode and complex mode can reduce China's CO_2 emissions of production (Hao et al. 2020), and the rise of GVC participation index in high-tech manufacturing has a more significant CO_2 emission reduction effect (Chang et al. 2020). Furthermore, the industrial structure upgrading effect brought about by the extension of the GVC production length is helpful for reducing the CO_2 emissions of the manufacturing industry (Zhao and Yang 2020). As Chinese manufacturing industry is deeply participating in GVC, the continuous improvement of technology (Wu and Pan 2018), the gradual optimization of the factor structure (Yu and Tian 2019), and the increasingly stringent environmental regulations (Zhang and Wei 2014) will significantly reduce CO_2 emissions in China's production (Lan and Xia 2020; Chuanwang et al. 2019) .

The third conclusion is the U-shaped relationship between GVC and CO_2 emissions. According to the Environmental Kuznets Curve (EKC) model (Grossman and Krueger 1995), domestic and foreign scholars have studied the CO_2 emission reduction effects of manufacturing industry, and found that as the participating degree of GVC deepens, CO_2 emissions will also show a U-shaped change. For example, when the economy is at the low end of the GVC position index, due to the scale effect and the industrial structure effect, the rise of the GVC position index has a promoting effect on CO_2 emissions. But with the development of technology, production gradually shifts to a high value-added and low CO_2-emission mode, The level of CO_2 emissions will show a downward trend (Xu et al. 2020). Meanwhile, the CO_2 emission reduction effect of GVC participation index will continue to be weaken. This is because when the leader country of the GVC see the development of the middle and downstream countries as a threat, they will prevent them from achieving GVC upgrades through technical barriers and other methods, and then lock the middle and downstream countries in the low-end GVC production links with high CO_2 emissions (Humphrey and Schmitz 2010), which will turn the GVC into "global pollution chains" (Duan et al. 2020), in the end, the CO_2 emission reduction effect of participating in GVC will be suppressed (Cai et al. 2020). At the same time, there is also an inverted U-shaped relationship between the GVC production length and CO_2 emissions. Although China has passed the turning point, Chinese manufacturing has already paid huge environmental costs in the process of participating in GVC (Su and Thomson 2016), which means that to a certain extent, participating in GVC is a stumbling block on the road to CO_2 emission reduction (Lafang et al. 2020). In addition, affected by the participating in GVC, the technological level (Xie 2018), production scale (Grossman and Krueger 1995), factor structure (Huizheng et al. 2020), and output structure (Yuan et al. 2017) of China's equipment manufacturing industry may also show a U-shaped relationship with CO_2 emissions .

In summary, the research on the impact of participating in GVC on manufacturing CO_2 emissions has yielded fruitful results. However, the existing research still has three points that need to be expanded. First, the measurement methods for the degree of participating of GVC mainly stay in the two aspects of GVC position index and GVC participation index, it is impossible to comprehensively and scientifically describe the participating degree of GVC (Yuan and Qi et al. 2019). Secondly, it is still not clear enough of the CO_2 emission effect model of GVC, and the internal links between CO_2 emissions and related indicators need to be clarified. Lastly, few studies have explored the specific impact of participating in GVC on CO_2 emissions from the perspective of sub-sector of equipment manufacturing industry.

Based on this, our study contributes to the previous literature in the following three aspects: (1) According to the global input-output table, the GVC production length is decomposed from the perspectives of the destination and the source of the value-added. And we distinguish the different concepts of the GVC production length, GVC simple production length, the GVC production length returned to the exporting country and the pure foreign GVC production length, which will help to comprehensively describe the situation of the equipment manufacturing industry in GVC and analyze the different results caused by different participating modes. (2) We update the analysis of environmental pollution and supply models, establish a CO_2 emission effect model of the GVC, obtain relevant economic indicators affecting CO_2 emissions. (3) We apply the CO_2 emission effect model of GVC to a specific industry level, and deeply study the relationship between the GVC participation degree and the CO_2 emissions of the equipment manufacturing industry, which will help to find the effective measures to achieve CO_2 emission reduction targets while deeply participating in the GVC.

Theoretical model

Refer to the environmental pollution and supply model constructed by Antweiler et al. (2001), this part bases on the theory of perfect competition, introduces the effect function of the impact of GVC on production, and constructs a CO_2 emission effect model with participating in GVC.

Now suppose:

(1) There are only two industries in the world, namely industry 1 and industry 2, of which industry 1 is a high-CO_2 industry and industry 2 is other industries. Then the world only produces two products, that is, industry 1 produces product X and industry 2 produces product Y. In addition, the production process of the two types of products obeys the principle of constant return to scale.

(2) Product X is a high-CO_2 product, that is, the production of product X will discharge a large amount of pollutants. Y is a low-CO_2 product, that is, the production of Y product does not emit any pollutants.

(3) Pollutants only consider CO_2 emissions and ignore other environmental effects.

(4) The production only need two factors, they are labor (L) and capital (K).

(5) In an open economy with complete market competition, both industry 1 and industry 2 participate in the international division of labor.

Suppose the production function of potential output in the economy is:

$$S = F(K, L) \tag{1}$$

In Equation (1), *F* is the production function, *S* is the total output of the industry, *K* is the capital input, and *L* is the labor input. Since the production of products will be affected by internal and external elements, the actual output will be lower than the potential output. Therefore, assume that the internal element that affects production is only the factor input ratio (*G*), that is, the ratio of capital input (*K*) to labor input (*L*); the external element that affects production is only the government's regulation of reducing CO_2 emissions, in this case, r represents the rate of decrease of output. Since the input of reducing CO_2 emissions will inhibit the increase of CO_2 emissions, the level of CO_2 emissions (CO_2 emissions per unit of output) can be expressed as $\varphi(r)=\frac{1}{T}(1-r)^{\frac{1}{\alpha}}$. Among them, $\varphi(r)$ is a decreasing function of *r*; the reciprocal form of production technology level (*T*) represents the inhibitory effect of technological improvements on CO_2 emissions; and $0<\alpha<1, \varphi'(r)<0, \varphi''(r)>0$.

Then the actual production function of product *X* is:

$$S_X = G_X(1-r)F(K_X, L_X) \tag{2}$$

The CO_2 emissions during the production of product is:

$$C=\varphi(r)F(K_X, L_X)=\frac{1}{T}(1-r)^{\frac{1}{\alpha}}F(K_X, L_X) \tag{3}$$

Since industry 1 participates in the international division of production when producing *X*, the effect of participating in GVC on production is $\omega(V)$. At this time, the actual production function of product *X* is:

$$S_X = G_X(1-r)F(K_X, L_X)\omega(V) \tag{4}$$

Incorporating formula 3 into formula 4, the relationship between actual production level of product *X* and CO_2 emissions can be obtained:

$$S_X = G_X(TC)^{\alpha}F(K_X, L_X)^{1-\alpha}\omega(V) \tag{5}$$

Since CO_2 emissions will cause negative externalization to the society, corresponding opportunity costs must be paid, so the tax rate for CO_2 emissions is set to γ. According to the principle of minimizing the cost of enterprises, under normal circumstances, enterprises will choose the optimal arrangement of potential output and CO_2 emission levels to achieve the lowest production cost of product. So we can construct the following function:

$$\begin{gathered}\min_{C}\{E(E_K, E_L)F(K_X, L_X)+\gamma TC\} \\ s.t. G_X(TC)^{\alpha}F(K_X, L_X)^{1-\alpha}\omega(V)=1\end{gathered} \tag{6}$$

Among them, $E(E_K, E_L)$ is the unit production cost of the potential output of product *X*, and E_K、E_L is the production cost of capital and labor respectively.

By constructing a Lagrangian function, we can obtain the derivation of CO_2 emission *C* and output $F(K_X, L_X)$ respectively:

$$\begin{gathered}\gamma T = -\alpha\theta G_X T^{\alpha}C^{\alpha-1}F(K_X, L_X)^{1-\alpha}\omega(V) \\ E=-(1-\alpha)\theta G_X T^{\alpha}C^{\alpha}F(K_X, L_X)^{-\alpha}\omega(V)\end{gathered} \tag{7}$$

Among them, θ is the Lagrangian multiplier. Then divide the two formulas in Equation (7) to obtain the cost minimization conditions for the production of *X* products by the enterprise.

$$E=\frac{\gamma(1-\alpha)TC}{\alpha F(K_X, L_X)} \tag{8}$$

Under perfectly competitive market conditions, the result of market competition is in line with Pareto optima. Then the net profit of the production of *X* product must be zero, so the profit function of *X* product is set as $\Pi = P_X S_X - EF(K_X, L_X) - \gamma TC$, where P_X is the relative price of *X* product relative to *Y* product, and the price of *Y* product is defined as 1, we can obtain:

$$P_X S_X = EF(K_X, L_X) + \gamma TC \tag{9}$$

Combining Equation (8) with Equation (9), we obtain:

$$S_X = \frac{\gamma TC}{\alpha P_X} \tag{10}$$

Then, the CO_2 emission level is:

$$\varphi(r) = \frac{C}{S_X} = \frac{\alpha P_X}{\gamma T} \tag{11}$$

The CO_2 emission function in Equation (3) can be rewritten as:

$$C = \varphi(r) F(K_X, L_X) = \frac{\alpha P_X}{\gamma T} \cdot \frac{S_X}{G_X (1-r)\omega(V)} \tag{12}$$

Equation (12) is the decomposition model of the CO_2 emission effect of product *X* participating in the GVC. After taking the logarithm of both sides, we obtain:

$$\ln C = \ln\left(\frac{\alpha P_X}{\gamma}\right) - \ln T + \ln S_X - \ln G_X - \ln(1-r) - \ln \omega(V) \tag{13}$$

Among them, $\ln\left(\frac{\alpha P_X}{\gamma}\right)$ is a constant term. As shown in Equation (13), the sign of production scale (*S*) is positive, which means that as the production scale expands, CO_2 emissions will increase; the sign of technical level (*T*), factor structure (*G*), and policy regulations (*r*) is negative, which means that CO_2 emissions will be reduced due to the improvement of technology, factor structure and policy regulations; and it is expected that the increase of the GVC participating level will also have a negative effect on CO_2 emissions.

Methodology and data

GVC production length decomposition model

According to the calculation method of Zhi et al. (2017a), this article will track the destinations and sources of value-added, and analyze GVC participation from forward and backward GVC production lengths. The process is as follows:

Divide the world into three parts: country *A*, country *B* and other countries (*R*). Each country has two industrial sectors: Industry 1 and Industry 2. Then, the world input-output table will be reflected in Table 1.

Table 1 World input-output

Country	Intermediate Use			Final Demand			Total
	A	B	R	A	B	R	Output

table

Country	Industry	1	2	1	2	1	2				
A	1	Z_{11}^{AA}	Z_{12}^{AA}	Z_{11}^{AB}	Z_{12}^{AB}	Z_{11}^{AR}	Z_{12}^{AR}	Y_1^{AA}	Y_1^{AB}	Y_1^{AR}	X_1^A
	2	Z_{21}^{AA}	Z_{22}^{AA}	Z_{21}^{AB}	Z_{22}^{AB}	Z_{21}^{AR}	Z_{22}^{AR}	Y_2^{AA}	Y_2^{AB}	Y_2^{AR}	X_2^A
B	1	Z_{11}^{BA}	Z_{12}^{BA}	Z_{11}^{BB}	Z_{12}^{BB}	Z_{11}^{BR}	Z_{12}^{BR}	Y_1^{BA}	Y_1^{BB}	Y_1^{BR}	X_1^B
	2	Z_{21}^{BA}	Z_{22}^{BA}	Z_{21}^{BB}	Z_{22}^{BB}	Z_{21}^{BR}	Z_{22}^{BR}	Y_2^{BA}	Y_2^{BB}	Y_2^{BR}	X_2^B
R	1	Z_{11}^{RA}	Z_{12}^{RA}	Z_{11}^{RB}	Z_{12}^{RB}	Z_{11}^{RR}	Z_{12}^{RR}	Y_1^{RA}	Y_1^{RB}	Y_1^{RR}	X_1^R
	2	Z_{21}^{RA}	Z_{22}^{RA}	Z_{21}^{RB}	Z_{22}^{RB}	Z_{21}^{RR}	Z_{22}^{RR}	Y_2^{RA}	Y_2^{RB}	Y_2^{RR}	X_2^R
Value-added		Va_1^A	Va_2^A	Va_1^B	Va_1^B	Va_1^R	Va_2^R				
Total Input		$(X_1^A)'$	$(X_2^A)'$	$(X_1^B)'$	$(X_2^B)'$	$(X_1^R)'$	$(X_2^R)'$				

Matrix Z represents the intermediate inputs produced in one country and used in another country; vector Y represents the final product produced in one country and used in another country; vector X represents the total output of one country; vector Va represents one Country's direct value added.

Suppose the input coefficient matrix is $A = Z\hat{X}^{-1}$, $\hat{x}$ represents the diagonal matrix of X, at this time, $V = Va\hat{X}^{-1}$. And the total output X can be expressed as:

$$X = AX + Y = A^D X + Y^D + A^F X + Y^F = A^D X + Y^D + E \tag{14}$$

Y represents the sum of final products used in a country from other countries, A^D represents the domestic input coefficient, Y^D represents the total domestic final products consumed by each country, A^F represents the import input coefficient, Y^F represents the sum of final products exported, and E represents total exports. According to the Leontief inverse matrix (B), we can rewrite Equation(14):

$$\begin{aligned} X &= BY = (I - A)^{-1} Y = (I - A^D)^{-1} Y^D + (I - A^D)^{-1} E \\ &= B^D Y^D + B^D E = B^D Y^D + B^D Y^F + B^D A^F X \end{aligned} \tag{15}$$

Among them, $B^D = (I - A^D)^{-1}$ represents the domestic Leontief inverse matrix. Based on this, the relationship between the value-added and the final product in Table 1 is:

$$Va' = \hat{V}X = \hat{V}BY \tag{16}$$

It can be seen that the initial input (value-added) of an industry can only be absorbed by the final product of the same industry. Therefore, the equation for the production process involved in the value-added can be summarized as follows:

$$\hat{V}\hat{Y} + \hat{V}A\hat{Y} + \hat{V}AA\hat{Y} + \cdots = \hat{V}(I + A + AA + \cdots)\hat{Y} = \hat{V}(I - A)^{-1}\hat{Y} = \hat{V}B\hat{Y} \tag{17}$$

$\hat{V}B\hat{Y}$ matrix represents the sum of value-added in all production stages, each element of which represents the value-added from an industry in one country, and the value-added is directly or indirectly used by an industry in another country to produce final products.

Take the production length of each stage as the weight and add it up to get the total output of a specific industrial department, we obtain:

$$\begin{aligned} &\hat{V}\hat{Y} + 2\hat{V}A\hat{Y} + 3\hat{V}AA\hat{Y} + \cdots = \hat{V}(I + 2A + 3AA + \cdots)\hat{Y} \\ &= \hat{V}(B + AB + AAB + \cdots)^{-1}\hat{Y} = \hat{V}BB\hat{Y} \end{aligned} \tag{18}$$

Therefore, the average production length of the value-added in the final product is:

$$PLvy = \frac{\hat{V}BB\hat{Y}}{\hat{V}B\hat{Y}} \tag{19}$$

The average production length based on the forward industry linkage is:

$$PLv = \frac{\hat{V}BBY}{\hat{V}BY} = \frac{\hat{V}BX}{\hat{V}X} \tag{20}$$

Equation (20) measures the amount of supplementary value-added per unit of industry once, in which the value-added of each industry can be seen as a whole. At this time, the longer the forward production length is, the more downstream production stages the value-added participates in as a substitute, and the higher its upstream production position is.

The production length based on the backward industry linkage is:

$$PLy = \frac{VBB\hat{Y}}{VB\hat{Y}} \tag{21}$$

Equation (21) measures the total value-added input of final product in a specific industry. At this time, the longer the backward production length is, the more upstream production stages of a particular final product has, the lower the downstream production position of the product is.

According to the decomposition framework of value-added and final products proposed by Zhi et al. (2017b), the production activities of a country can be broken down into 5 parts according to the different situation of cross-border production activities:

$$\begin{aligned} \hat{V}B\hat{Y} &= \hat{V}B^D\hat{Y}^D + \hat{V}B^D\hat{Y}^F + \hat{V}B^D A^F B\hat{Y} \\ &= \underbrace{\hat{V}B^D\hat{Y}^D}_{(1)-V\_D} + \underbrace{\hat{V}B^D\hat{Y}^F}_{(2)-V\_RT} + \underbrace{\hat{V}B^D A^F B^D\hat{Y}^D}_{(3a)-V\_GVC\_S} + \underbrace{\hat{V}B^D A^F (B\hat{Y} - B^D\hat{Y}^D)}_{(3b)-V\_GVC\_C} \\ &= \underbrace{\hat{V}B^D\hat{Y}^D}_{(1)-V\_D} + \underbrace{\hat{V}B^D\hat{Y}^F}_{(2)-V\_RT} + \underbrace{\hat{V}B^D A^F B^D\hat{Y}^D}_{(3a)-V\_GVC\_S} + \underbrace{\hat{V}B^D (A^F B)^D \hat{Y}}_{(4a)-V\_GVC\_D} + \underbrace{\hat{V}B^D[(A^F B)^F \hat{Y} - A^F B^D \hat{Y}^D]}_{(4b)-V\_GVC\_F} \end{aligned} \tag{22}$$

In Equation (22), (1)The first part is the domestic value-added, which refers to the part of domestically produced goods that are ultimately consumed domestically, represented by *V_D*. (2) Part 2 represents the Ricardo trade part, that is, the final products exporting to foreign countries are directly consumed, which is only cross-border once, denoted by *V_RT*. (3)The part representing cross-border production activities is divided into simple cross-border production activities and complex cross-border production activities. Simple cross-border production activity refers to the part of the intermediate product produced in one country and directly used by the importing country for production and consumption, the production activity is only cross-border once, denoted as *V_GVC_S*. Complex cross-border production activity refers to the part of intermediate goods produced in one country that are used by the importing country for production and exported to a third country, denoted as *V_GVC_C*. (4) The complex cross-border production activities involve two categories according to whether they return to the exporting country. Among them, 4a is the part returned to the exporting country and absorbed by the exporting country, denoted by *V_GVC_D*. 4b is the part that is indirectly absorbed by the importing country and exported to other trading partner countries after being processed, denoted by *V_GVC_F*.

According to this, the GVC production length in Equation 19 is divided into five parts:

$$
\begin{aligned}
PLvy &= \underbrace{\frac{\hat{V}B^D B^D \hat{Y}^D}{\hat{V}B^D \hat{Y}^D}}_{(1)-PL\_D} + \underbrace{\frac{\hat{V}B^D B^D \hat{Y}^F}{\hat{V}B^D \hat{Y}^F}}_{(2)-PL\_RT} + \underbrace{\frac{\hat{V}BB\hat{Y} - \hat{V}B^D B^D \hat{Y}^D}{\hat{V}B^D A^F B\hat{Y}}}_{(3)-PL\_GVC} \\
&= \underbrace{\frac{\hat{V}B^D B^D \hat{Y}^D}{\hat{V}B^D \hat{Y}^D}}_{(1)-PL\_D} + \underbrace{\frac{\hat{V}B^D B^D \hat{Y}^F}{\hat{V}B^D \hat{Y}^F}}_{(2)-PL\_RT} + \underbrace{\frac{\hat{V}B^D B^D A^F B^D \hat{Y}^D + \hat{V}B^D A^F B^D B^D \hat{Y}^D}{\hat{V}B^D A^F B\hat{Y}}}_{(3a)-PL\_GVC\_S} \\
&+ \underbrace{\frac{\hat{V}B^D B^D A^F (B\hat{Y} - B^D \hat{Y}^D)}{\hat{V}B^D A^F (B\hat{Y} - B^D \hat{Y}^D)}}_{(4a)-PL\_GVC\_D} + \underbrace{\frac{\hat{V}B^D A^F (BB\hat{Y} - B^D B^D \hat{Y}^D)}{\hat{V}B^D A^F (B\hat{Y} - B^D \hat{Y}^D)}}_{(4b)-PL\_GVC\_F}
\end{aligned}
\tag{23}
$$

Similarly, as shown in Equations 24 and 25, the forward production length (*PLv*) and the backward production length (*PLy*) can also be divided into five parts. Among them, the part that participates in GVC activities include the GVC production length (*PLv_GVC*, *PLy_GVC*), the simple GVC production length (*PLv_GVC_S*, *PLy_GVC_S*), the GVC production length returning to the exporting country (*PLv_GVC_D*, *PLy_GVC_D*) and the pure foreign GVC production length (*PLv_GVC_F*, *PLy_GVC_F*). The decomposition model of production length is shown in Fig. 1.

$$
\begin{aligned}
PLv &= \underbrace{\frac{\hat{V}B^D B^D Y^D}{\hat{V}B^D Y^D}}_{(1)-PLv\_D} + \underbrace{\frac{\hat{V}B^D B^D Y^F}{\hat{V}B^D Y^F}}_{(2)-PLv\_RT} + \underbrace{\frac{\hat{V}BBY - \hat{V}B^D B^D Y^D}{\hat{V}B^D A^F BY}}_{(3)-PLv\_GVC} \\
&= \underbrace{\frac{\hat{V}B^D B^D Y^D}{\hat{V}B^D Y^D}}_{(1)-PLv\_D} + \underbrace{\frac{\hat{V}B^D B^D Y^F}{\hat{V}B^D Y^F}}_{(2)-PLv\_RT} + \underbrace{\frac{\hat{V}B^D B^D A^F B^D Y^D + \hat{V}B^D A^F B^D B^D Y^D}{\hat{V}B^D A^F BY}}_{(3a)-PLv\_GVC\_S} \\
&+ \underbrace{\frac{\hat{V}B^D B^D A^F (BY - B^D Y^D)}{\hat{V}B^D A^F (BY - B^D Y^D)}}_{(4a)-PLv\_GVC\_D} + \underbrace{\frac{\hat{V}B^D A^F (BBY - B^D B^D Y^D)}{\hat{V}B^D A^F (BY - B^D Y^D)}}_{(4b)-PLv\_GVC\_F}
\end{aligned}
\tag{24}
$$

$$
\begin{aligned}
PLy &= \underbrace{\frac{VB^D B^D \hat{Y}^D}{VB^D \hat{Y}^D}}_{(1)-PLy\_D} + \underbrace{\frac{VB^D B^D \hat{Y}^F}{VB^D \hat{Y}^F}}_{(2)-PLy\_RT} + \underbrace{\frac{VBB\hat{Y} - VB^D B^D \hat{Y}^D}{VB^D A^F B\hat{Y}}}_{(3)-PLy\_GVC} \\
&= \underbrace{\frac{VB^D B^D \hat{Y}^D}{VB^D \hat{Y}^D}}_{(1)-PLy\_D} + \underbrace{\frac{VB^D B^D \hat{Y}^F}{VB^D \hat{Y}^F}}_{(2)-PLy\_RT} + \underbrace{\frac{VB^D B^D A^F B^D \hat{Y}^D + VB^D A^F B^D B^D \hat{Y}^D}{VB^D A^F B\hat{Y}}}_{(3a)-PLy\_GVC\_S} \\
&+ \underbrace{\frac{VB^D B^D A^F (B\hat{Y} - B^D \hat{Y}^D)}{VB^D A^F (B\hat{Y} - B^D \hat{Y}^D)}}_{(4a)-PLy\_GVC\_D} + \underbrace{\frac{VB^D A^F (BB\hat{Y} - B^D B^D \hat{Y}^D)}{VB^D A^F (B\hat{Y} - B^D \hat{Y}^D)}}_{(4b)-PLy\_GVC\_F}
\end{aligned}
\tag{25}
$$

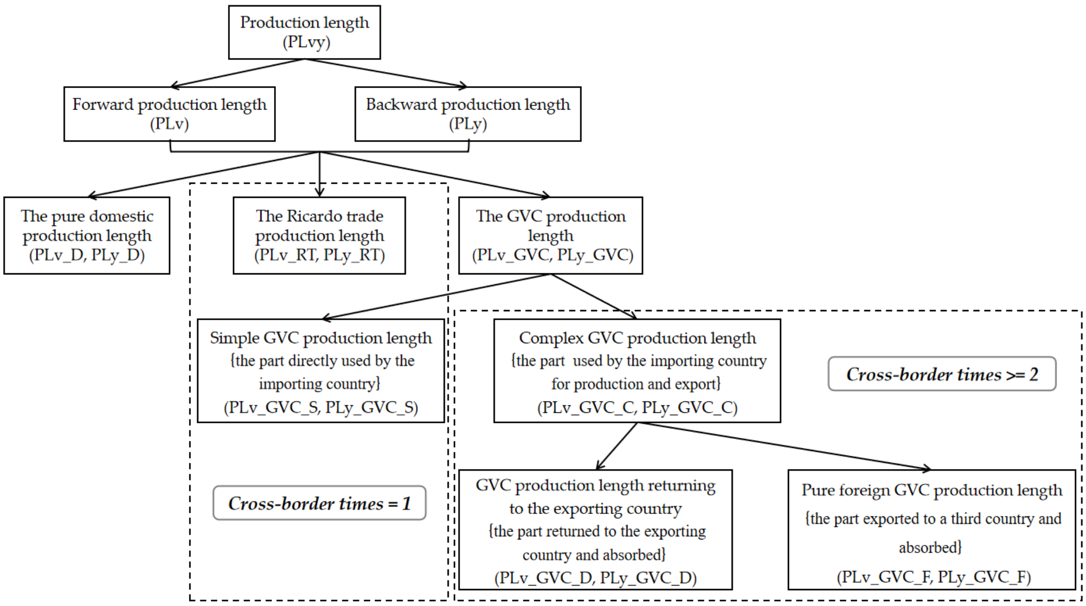


Fig. 1 The decomposition model of production length

STIRPAT model

In order to test the real impact of the indicators in the theoretical model, this part studies the specific impact of GVC production length on CO_2 emissions of China's equipment manufacturing industry by constructing a STIRPAT (Stochastic Impacts by Regression on PAT) model. The prototype of the STIRPAT model is the IPAT model, which was first proposed by Enrlich and Holden, and has been widely used in the field of environmental contamination research (Hofmann et al. 2016). In the IPAT model, the environmental pressure (*I*) is determined by the population size (*P*), per capita assets (*A*), and technology level (*T*). Its general form is as follows:

$$I = PAT \tag{26}$$

As shown in Equation (26), the IPAT model reflects the impact of population growth and other factors on environmental pressure. However, when the IPAT model describes the relationship between environmental impacts and various driving factors, it can only reflect changes in the same proportion, limiting other possible impact results, and the model cannot perform hypothesis testing, so York and Dietz proposed the STIRPAT model ,which is:

$$I_i = aP_i^b A_i^c T_i^d e_i \tag{27}$$

Take the logarithm of both sides of the Equation to rewrite Equation (27) into the additive mode:

$$\ln I_i = a + b\ln P_i + c\ln A_i + d\ln T_i + e_i \tag{28}$$

The STIRPAT model converts the IPAT statistical model to an ordinary linear model, which can be hypothesized tested by statistical methods, and the different impact strength of each impact factor can be estimated. The independent variables *P*, *A* and *T* can be replaced with other variables related to the main research object (Li 2019). Therefore, based on the classic STIRPAT model and the actual situation of the impact of participating in GVC on CO_2 emissions, this paper improves and replaces some of the influencing factors, and finally builds the following empirical model:

$$\ln C_{it} = \beta_0 + \beta_1 \ln V_{it} + \beta_2 \ln Policy_{it} + \beta_3 \ln Scale_{it} + \beta_4 \ln G\_factor_{it} + \beta_5 \ln T\_fdi_{it} + \beta_6 \ln T\_Rd_{it} + \varepsilon_{it} \quad (29)$$

In Equation (29), the explained variable *C* represents the CO_2 emissions of each sub-industry of China's equipment manufacturing industry, which is a substitute for the environmental pressure in the IPAT model; *V* represents the core explanatory variables related to the GVC, including forward and backward GVC production length (*PLv_GVC*, *PLy_GVC*) and its decomposed parts; *Policy* represents the policy regulation, which is expressed by the amount of industrial pollution control investment based on the method of Peng and Li (2013),and the weight is the ratio of the total investment in fixed assets of equipment manufacturing industry to China's total investment in fixed assets, then the industrial pollution control investment is calculated according to China's total pollution control investment; *Scale* represents the production scale, instead of the population size in the original IPAT model, it is measured by per capita output value; *G_factor* is the factor structure, replacing the per capita assets in the original IPAT model, expressed by the ratio of the total fixed assets of industrial enterprises above designated size to the average number of industrial employees in each industry; in this article, the technical level in the original IPAT model is jointly replaced by *T_fdi* and *T_Rd*, and using the method of Xu (2019), foreign direct investment (*T_fdi*) is measured by the proportion of total assets of Hong Kong, Macao, Taiwan and foreign-invested industrial enterprises in total assets of all industrial enterprises above designated size, and R&D investment (*T_Rd*) measured by the R&D expenditures of various industries; β_0 represents a constant term; β_1 to β_7 represent the coefficient of each variables, ε represents a random disturbance term, *i* represents an industry, and *t* represents time.

Data Sources

Based on the International Standard Industrial Classification (ISIC Rev.4) and China's National Economic Standard Industrial Classification (GB/4757-2002), this article merges China's equipment manufacturing industry into five sub-industries, and selects the sample period from 2000 to 2014. Among them, the CO_2 emission data is the original data of the latest environmental account released by the WIOD database in 2019; the data of the forward GVC production length, the backward GVC production length and the value-added of each industry are all calculated by the input-output account released by WIOD in 2016; R&D expenditure data comes from the "Statistical Yearbook of Scientific and Technological Activities of Industrial Enterprises"; the rest of the data all comes from the "China Statistical Yearbook".

Empirical results

The GVC production length of China's equipment manufacturing industry

The results of the forward and backward GVC production length of China's equipment manufacturing industry is shown in Fig. 2 and Fig. 3. China's equipment manufacturing industry has become deeply participating in GVC, and the change trend of forward and backward GVC production length is similar, but the backward GVC production length is always longer than the forward GVC production length. In 2001, the production length of the forward and backward GVC production length increased rapidly, which thanks to the tremendous progress that China made after joining the WTO in 2000, the convenience of participating in the international division of production has been promoted, and the technology spillovers from developed countries has increased. After a difficult growth process, the

GVC participating level of China's equipment manufacturing industry achieved a major leap again in 2009. Comparing the GVC production length under different participating modes, the largest increase part is the GVC production length returning to the exporting country, followed by the pure foreign GVC production length. The variation of the GVC production length and the simple GVC production length is almost the same. It shows that the impetus provided by participating in GVC is far greater than that of China's independent research and development.

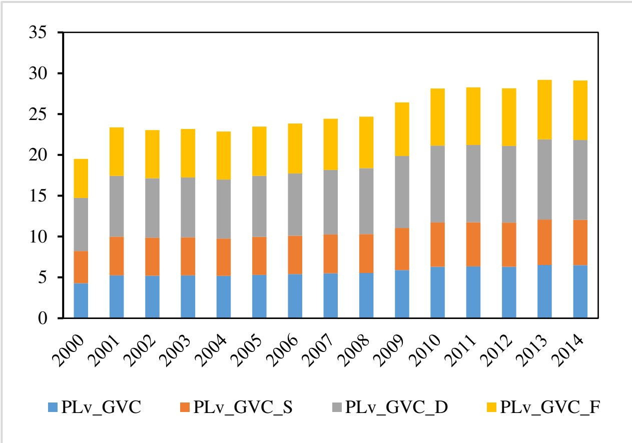


Fig.2 The forward GVC production length of China's equipment manufacturing industry

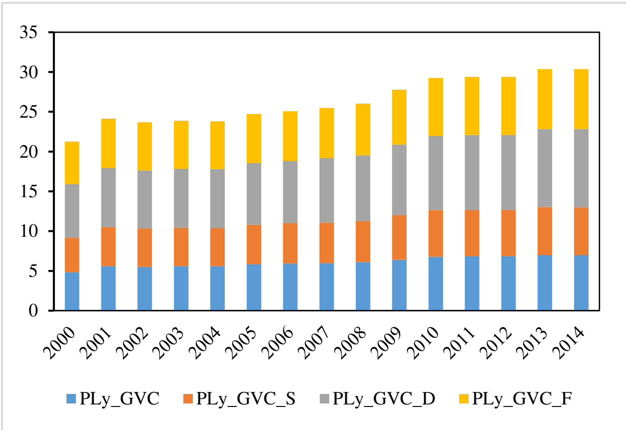
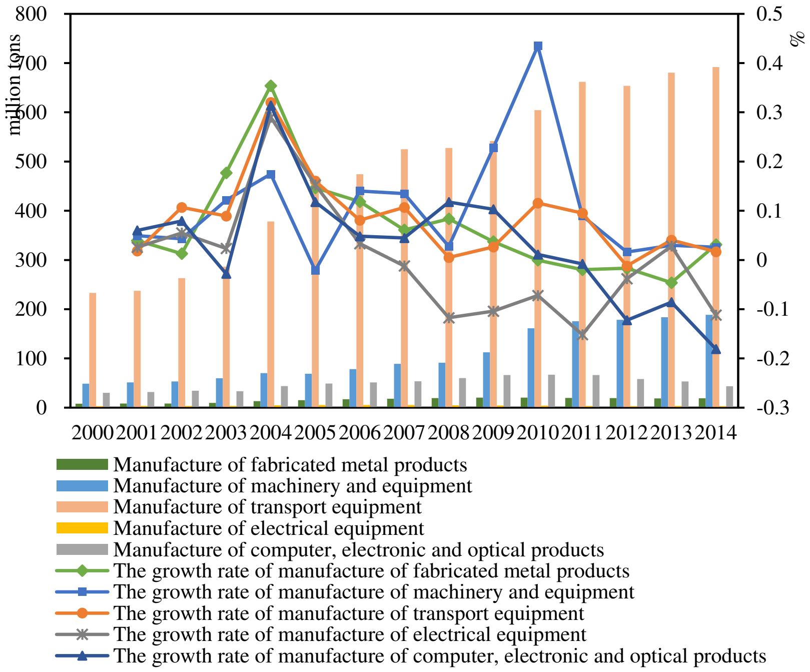


Fig.3 The backward GVC production length of China's equipment manufacturing industry

CO_2 emissions of China's equipment manufacturing industry

The CO_2 emissions of China's equipment manufacturing industry show obvious characteristics of industry clusters and stage distribution (Fig. 4). At first, the characteristics of industry clusters of CO_2 emissions mainly reflect in the transportation equipment manufacturing industry. The CO_2 emissions of the transportation equipment manufacturing industry accounted for about 73.19% of the total CO_2 emissions of the equipment manufacturing industry. The CO_2 emissions in 2014 reached 6.918 million tons, which is the main reason for the significant increase of the CO_2 emissions of the equipment manufacturing industry. The machinery and equipment manufacturing industry ranked second, and its CO_2 emissions increased rapidly in 2010, with an average annual proportion of about 15.76%; computer, electronic and optical product manufacturing ranked third, with an average annual proportion of 7.92%; fabricated metal products industry and electrical equipment manufacturing industry followed closely, with an average annual proportion of 2.43% and 0.7%, respectively. In contrast, the CO_2 emissions of the transportation equipment manufacturing industry far exceed those of other industries, leading to the CO_2 emissions of the medium-tech manufacturing industries about 9 times than that of high-tech industries. Meanwhile, the CO_2 emission trend of China's equipment manufacturing industry is mainly divided into three stages. The first stage is the slow growth stage from 2000 to 2003. In this stage, the CO_2 emissions of various industries are slowly increasing, and the annual growth rate is maintained at a relatively stable level. The total CO_2 emissions in 2003 is about 392.98 million tons. The second stage was from 2004 to 2011. Thanks to the strong support of the Chinese government for the equipment manufacturing industry, the output value of the equipment manufacturing industry in this stage increased rapidly, resulting in a substantial increase in CO_2 emissions, which reached a peak in 2011 at approximately 927.00 million tons. The third stage is the period of fluctuating growth from 2012 to 2014. But except for the CO_2 emission growth rate of the fabricated metal products industry which rebounded in 2014, the CO_2 emission growth rate of other sub-sectors is decreasing. The CO_2 emissions of computer, electronic and optical products manufacturing industry and electrical equipment manufacturing industry also showed negative growth, indicating that China's equipment manufacturing industry has good prospects for CO_2 reduction.

Fig. 4 The CO_2 emission of China's equipment manufacturing industry from 2000 to 2014



The impact of the GVC production length on CO_2 emissions

This paper uses the panel data of China's equipment manufacturing industry from 2000 to 2014 to perform regression analysis on Equation (31). At first, in order to avoid endogenous problems, we applied the LLC test and ADF-Fisher test, the outcomes indicates that the panel data sets follow the stationary process (Table 2).

Table 2 Panel unit root test results

Variables	LLC Test	ADF Test	Variables	LLC Test	ADF Test

C	-1.7440	-2.7329	PLv_GVC_S	-4.1954	-2.9046
	(0.0406)	(0.0031)		(0.0000)	(0.0018)
Policy	-4.6917	-4.3130	PLv_GVC_D	-4.8818	-5.6982
	(0.0000)	(0.0000)		(0.0000)	(0.0000)
Scale	-4.5352	-3.8243	PLv_GVC_F	-4.7051	-5.3724
	(0.0000)	(0.0001)		(0.0000)	(0.0000)
G_factor	-1.5983	-2.5289	PLy_GVC	-4.6544	-3.5775
	(0.0550)	(0.0057)		(0.0000)	(0.0002)
T_fdi	-3.9857	-2.4197	PLy_GVC_S	-4.2320	-3.5288
	(0.0000)	(0.0078)		(0.0000)	(0.0002)
T_Rd	-2.0939	-2.3833	PLy_GVC_D	-9.5204	-6.6370
	(0.0181)	(0.0086)		(0.0000)	(0.0000)
PLv_GVC	-4.0849	-4.3532	PLy_GVC_F	-5.4928	-6.4258
	(0.0000)	(0.0000)		(0.0000)	(0.0000)

Note: The P value is in parentheses

.

Then, according to the results of the F test of the panel data, the fixed effects model is better than the mixed regression model. Finally, because the original hypothesis of the Hausman test is that there is a random effect, and the results of the Hausman test in this article reject the null hypothesis, indicating that the fixed effect model is better than the random effect model. Based on this, the empirical estimation results are as follows.

The first three columns in Table 3 are the regression results with only control variables added. The results show that policy regulation, industrial scale, factor structure, foreign direct investment and R&D investment all have a significant impact on CO_2 emissions. However, the coefficient of determination R^2 in column (1) is only 0.558, which is much lower than 0.757 in column (2), indicating that 19.9% of CO_2 emissions changes are caused by individual differences that do not change over time. The fixed effect model is more accurate in estimating the indicators in this article. After continuing to add annual dummy variables in column (3), the impact of policy regulation and foreign investment on CO_2 emissions has become significant, and the coefficient of determination R^2 has increased to 0.853, indicating a 9.6% change in CO_2 emissions of the equipment manufacturing industry can be explained by missing variables that change with time but not with industry.

Table 3 The impact of forward and backward production length and GVC production length on CO_2 emissions

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	RE	FE	FE	FE	FE	FE	FE
PLv				0.319			
				(0.540)			
PLy					-5.251***		
					(1.197)		
PLv_GVC						-3.723***	
						(1.092)	

PLy_GVC							-5.466***
							(1.658)
Policy	1.056***	-0.0747	-0.394***	-0.389***	-0.273**	-0.483***	-0.244**
	(0.324)	(0.0742)	(0.117)	(0.118)	(0.104)	(0.109)	(0.116)
Scale	-5.490***	0.956***	2.139***	2.128***	1.016*	2.541***	1.087
	(1.395)	(0.297)	(0.623)	(0.628)	(0.593)	(0.579)	(0.654)
G_factor	6.223***	-1.348***	-3.088***	-3.081***	-1.609**	-3.653***	-2.192***
	(1.431)	(0.398)	(0.785)	(0.790)	(0.753)	(0.733)	(0.768)
T_fdi	1.886***	0.0890	-0.885***	-0.919***	-0.288	-1.196***	-0.348
	(0.504)	(0.193)	(0.255)	(0.263)	(0.258)	(0.249)	(0.285)
T_Rd	-0.0304	0.483***	1.440***	1.477***	1.155***	1.385***	1.290***
	(0.187)	(0.177)	(0.254)	(0.262)	(0.227)	(0.231)	(0.237)
_cons	15.95***	1.240	-2.052	-2.413	7.006***	2.556	9.589**
	(3.371)	(0.773)	(1.396)	(1.532)	(2.387)	(1.855)	(3.755)
Industry FE	YES	YES	YES	YES	YES	YES	YES
Year FE	NO	NO	YES	YES	YES	YES	YES
R-Squared	0.558	0.757	0.853	0.854	0.894	0.881	0.879
Hausman Test	67.26/0.0000						
N	75	75	75	75	75	75	75

Note: The robust standard errors in parentheses, ***, **, and * indicate significant at the level of 1%, 5%, and 10% respectively.

With the acceleration of globalization, the impact of participating in GVC on CO_2 emissions cannot be ignored. Since production length variables change with time and individual differences, columns (4) to (7) in Table 3 is based on column (3) and added variables reflecting the production length of China's equipment manufacturing industry to test the specific impact of GVC production length on CO_2 emissions. Except for the forward production length, the impact of the backward production length, the forward GVC production length and the backward GVC production length on the CO_2 emissions of the equipment manufacturing industry have all passed the test at a significant level of 1%, and the coefficients of the three are all negative, which means that for every 1% increase in the backward production length, the forward GVC production length and the backward GVC production length, the level of CO_2 emissions will drop by about 5.3%, 3.7%, and 5.5%, respectively. The CO_2 emission reduction effect of the GVC is obvious, which further supports the derivation in the previous model. Column (6) shows that the extension of the forward GVC production length can effectively reduce CO_2 emission, indicating that the equipment manufacturing industry has achieved technological improvement through imitation, learning and secondary innovation in the process of moving upstream to the international division of production. But this reduction is still not enough to drive the overall transformation of the CO_2 emissions of intermediate products in the equipment manufacturing industry, making the CO_2 emission reduction effect from the perspective of forward production length not obvious, which also shows that the production technology of industrial intermediate products of China's domestic equipment manufacturing industry is still not environmentally friendly, and the improvement of clean technology in the domestic equipment manufacturing industry has stuck in a "bottleneck period". It can be seen from columns (5) and (7) that the CO_2 emission reduction effect of the backward production length and the backward GVC production length is similar, both are greater than the result of the forward GVC production length. It proves that while the participation of China's equipment manufacturing industry in GVC activities has increased, the clean level of final product production technology has been greatly improved, and it has gradually moved from a low-tech, high-CO_2 production stage to a high-tech, low-CO_2 production stage.

According to the data in each column in Table 4, whether it is the forward GVC production length or the backward GVC production length, the extension of the simple GVC production length has the best reduction effect on CO_2 emissions, both are significantly negative at the 1% level. However, the length of complex GVC production length has little effect on CO_2 emissions, and only the backward pure foreign GVC production length has passed the test and has a positive effect on CO_2 emissions. This means that only one of the three types of intermediate products exported by China's equipment manufacturing industry has played a huge role in promoting CO_2 emission reduction.The first type is the intermediate products directly used and consumed by the importing country. The GVC production length is expressed as *PLv_GVC_S* and *PLy_GVC_S*. The CO_2 emissions of such products decrease with the extension of the production length, indicating that China's cleaner production technology for this type of product has been promoted. The second type is the intermediate product used by the importing country to produce and return to the exporting country. Its GVC production length is expressed as *PLv_GVC_D* and *PLy_GVC_D*. The poor production performance of this type of product indicates that even if the final products that meet domestic needs also needs to be processed by foreign companies before it is used. It further points out the urgency of China's equipment manufacturing industry to improve the level of production technology. The third type is intermediate products that are used by importing countries for production and exported to third countries, expressed as *PLv_GVC_F* and *PLy_GVC_F*. The extension of the production length of such products will promote the increase of CO_2 emissions. The reason is that the participation level of international production of China's equipment manufacturing industry is not high, the industry mainly participates in the GVC through simple processing and production links. The processing technology of complex intermediate products is still immature, when China processes and assembles imported high value-added intermediate imports, it keeps a large amount of CO_2 emissions in the country (Zhao and Yang 2020).

Table 4 The impact of the decomposition of the GVC production length on CO_2 emissions

Variables	Forward GVC production length			Backward GVC production length		
	（1）	（2）	（3）	（4）	（5）	（6）
PLv_GVC_S	-2.922***					
	(0.985)					
PLv_GVC_D		-0.120				
		(0.723)				
PLv_GVC_F			0.496			
			(0.666)			
PLy_GVC_S				-3.923***		
				(1.322)		
PLy_GVC_D					1.127	

	(1)	(2)	(3)	(4)	(5)	(6)
					(1.078)	
PLy_GVC_F						1.320*
						(0.800)
Policy	-0.489***	-0.391***	-0.393***	-0.272**	-0.419***	-0.402***
	(0.113)	(0.119)	(0.117)	(0.116)	(0.119)	(0.115)
Scale	2.463***	2.143***	2.064***	1.370**	2.095***	2.084***
	(0.591)	(0.630)	(0.634)	(0.636)	(0.624)	(0.614)
G_factor	-3.501***	-3.103***	-2.981***	-2.429***	-2.994***	-3.027***
	(0.744)	(0.797)	(0.801)	(0.764)	(0.789)	(0.773)
T_fdi	-1.186***	-0.889***	-0.792***	-0.524*	-0.870***	-0.792***
	(0.258)	(0.259)	(0.285)	(0.267)	(0.255)	(0.257)
T_Rd	1.452***	1.448***	1.394***	1.365***	1.432***	1.414***
	(0.236)	(0.260)	(0.262)	(0.237)	(0.253)	(0.250)
_cons	1.196	-1.811	-2.708	5.805*	-4.319	-8.783***
	(1.700)	(2.022)	(1.657)	(2.950)	(2.579)	(2.130)
Industry FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
R-Squared	0.875	0.853	0.854	0.875	0.856	0.860
N	75	75	75	75	75	75

Note: The robust standard errors in parentheses, ***, **, and * indicate significant at the level of 1%, 5%, and 10% respectively.

The impact of the relevant economic indicators on CO_2 emissions

Observing the data in Tables 3 and Table 4, we can see that policy regulations, factor structure, and foreign investment have a negative impact on CO_2 emissions, and scale effects and R&D investment will promote the increase of CO_2 emissions. In addition to R&D investment, the effects of other indicators on CO_2 emissions are in line with expected results. The specific analysis is as follows: (1) The coefficient of policy regulation is maintained at around -0.4, and the promotion of CO_2 emission reduction is not obvious. This is related to China's industrialization development stage during 2000-2011, and environmental regulation did not take effect until it is over. (2) The production scale has an increasing effect on CO_2 emissions, because in the process of joining the international division of production, China's equipment manufacturing industry has undertaken the transfer of high-CO_2 emission industries from developed countries, and production is mainly based on high-energy and high-polluting activities. The expansion of production scale will lead to an increase in CO_2 emissions, which is consistent with the reality. (3) The factor structure has a restraining effect on CO_2 emissions. The factor structure of China's equipment manufacturing industry is changing from labor-intensive to capital-intensive, and it is still in the process of moving towards technology-intensive. The prospects for reducing CO_2 emissions through the adjustment of the factor structure are great. (4) There is a significant negative correlation between foreign investment and CO_2 emissions, indicating that the clean technology learned from the investing country can inhibit CO_2 emissions with the spillover effect of FDI technology. (5) The effect of R&D investment on CO_2 emissions is positive and insignificant, which is consistent with the results of Wang et al. (2015). The reason is that, on the one hand, because the current Chinese enterprises cannot effectively allocate R&D resources, the actual investment in clean technology is much lower than expected; on the other hand, it is because the current level of CO_2 emission reduction technology of the equipment manufacturing industry is extremely low.

Robustness check

For the purpose of further examine the robustness of the empirical results, this paper removes 5% of the extreme values from both ends, and performs regression test on the sub-samples to eliminate the influence of non-randomness on the regression results (Table 5). The sample results are almost as same as the benchmark regression results, indicating that the research conclusions have strong robustness.

Table 5 Robustness test

Variables	Forward GVC production length				Backward GVC production length			
	（1）	（2）	（3）	（4）	（5）	（6）	（7）	（8）
PLv_GVC	-2.354**							
	(0.938)							
PLv_GVC_S		-2.280**						
		(0.934)						
PLv_GVC_D			-0.188					
			(0.740)					
PLv_GVC_F				0.304				
				(0.649)				
PLy_GVC					-2.795**			
					(1.405)			
PLy_GVC_S						-2.594**		
						(1.131)		
PLy_GVC_D							0.605	
							(0.985)	
PLy_GVC_F								1.079*
								(0.628)
Policy	-0.417***	-0.451***	-0.389***	-0.395***	-0.277**	-0.273**	-0.408***	-0.407***
	(0.111)	(0.114)	(0.119)	(0.117)	(0.128)	(0.124)	(0.119)	(0.194)
Scale	2.332***	2.358***	2.141***	2.108***	1.575**	1.580**	2.128***	2.138***
	(0.598)	(0.602)	(0.629)	(0.632)	(0.669)	(0.647)	(0.627)	(0.724)
G_factor	-3.338***	-3.288***	-3.105***	-3.044***	-2.552***	-2.564***	-3.061***	-3.096***
	(0.753)	(0.754)	(0.795)	(0.796)	(0.809)	(0.788)	(0.791)	(0.922)
T_fdi	-1.055***	-1.075***	-0.888***	-0.844***	-0.578*	-0.621**	-0.891***	-0.861***
	(0.252)	(0.256)	(0.258)	(0.272)	(0.292)	(0.271)	(0.257)	(0.311)
T_Rd	1.386***	1.396***	1.451***	1.419***	1.347***	1.388***	1.444***	1.440***

	(0.242)	(0.243)	(0.259)	(0.259)	(0.251)	(0.245)	(0.255)	(0.360)
_cons	1.004	0.613	-1.662	-2.503	-0.238	3.256	-3.310	-4.111**
	(1.803)	(1.723)	(2.081)	(1.705)	(3.617)	(2.676)	(2.484)	(3.504)
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
R-Squared	75	75	75	75	75	75	75	75
N	0.869	0.868	0.853	0.853	0.864	0.867	0.854	0.858

Note: The robust standard errors in parentheses, ***, **, and * indicate significant at the level of 1%, 5%, and 10% respectively.

Industry Heterogeneity Analysis

In order to investigate whether there is industry heterogeneity in the impact of participating in the GVC on CO_2 emissions of China's equipment manufacturing industry, referring to the method of Peng and Kuang (2019), the equipment manufacturing industry is divided into high-tech and medium-tech equipment manufacturing industry. Empirical test of the impact of the forward and backward GVC production length on CO_2 emissions has been conducted. High-tech industries include computer, electronic and optical product manufacturing, electrical equipment manufacturing industry and mechanical and equipment manufacturing industry, and medium-tech industries include fabricated metal products industry and transportation equipment manufacturing. The results are shown in Table 6 and Table 7.

Table 6 The impact of forward GVC production length on the CO_2 emissions

Variables	High-tech equipment manufacturing industry				Medium-technology equipment manufacturing industry			
	（1）	（2）	（3）	（4）	（5）	（6）	（7）	（8）
PLv_GVC	-2.189**				1.153***			
	(0.902)				(0.000132)			
PLv_GVC_S		-1.539**				1.183***		
		(0.749)				(0.000179)		
PLv_GVC_D			-1.725***				0.612***	
			(0.456)				(0.0000142)	
PLv_GVC_F				-1.858***				0.520***
				(0.528)				(0.0000127)
Policy	-0.636***	-0.700***	-0.730***	-0.821***	-0.182***	-0.169***	0.0685***	0.0382***
	(0.191)	(0.164)	(0.125)	(0.112)	(0.00000637)	(0.00000625)	(0.00000330)	(0.00000265)
Scale	1.636*	1.412	1.414	1.505	0.222***	0.279***	0.168***	0.312***
	(0.961)	(1.089)	(1.344)	(1.425)	(0.00000780)	(0.0000145)	(0.0000371)	(0.0000456)
G_factor	-2.491***	-2.098**	-2.030	-1.962	-1.175***	-1.232***	-0.571***	-0.772***
	(0.548)	(0.836)	(1.271)	(1.240)	(0.0000220)	(0.0000329)	(0.0000287)	(0.0000382)
T_fdi	0.221	0.215	0.346	0.138	-0.0890***	-0.0804***	0.283***	0.251***
	(0.277)	(0.249)	(0.281)	(0.333)	(0.00000681)	(0.00000642)	(0.00000299)	(0.00000473)

T_Rd	1.324***	1.400***	1.524***	1.557***	0.103***	0.112***	-0.0896***	-0.00307***
	(0.131)	(0.166)	(0.205)	(0.202)	(0.00000869)	(0.0000112)	(0.0000102)	(0.0000138)
_cons	3.250	2.635	4.072	3.603	2.205***	2.138***	2.735***	2.722***
	(3.644)	(3.380)	(3.238)	(3.081)	(0.0177)	(0.0177)	(0.0119)	(0.0135)
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
R-Squared	0.907	0.906	0.913	0.912	0.997	0.997	0.998	0.998
N	45	45	45	45	30	30	30	30

Note: The robust standard errors in parentheses, ***, **, and * indicate significant at the level of 1%, 5%, and 10% respectively.

Table 7 The impact of backward GVC production length on the CO_2 emissions

Variables	High-tech equipment manufacturing industry				Medium-technology equipment manufacturing industry			
	（1）	（2）	（3）	（4）	（5）	（6）	（7）	（8）
PLy_GVC	-5.848**				1.076***			
	(2.703)				(0.000220)			
PLy_GVC_S		-3.995**				1.235***		
		(2.037)				(0.0000566)		
PLy_GVC_D			-1.218**				0.469***	
			(0.550)				(0.0000982)	
PLy_GVC_F				-0.409				0.408***
				(1.101)				(0.00000618)
Policy	-0.608**	-0.575***	-0.710***	-0.790***	-0.196***	-0.189***	-0.124***	-0.155***
	(0.229)	(0.0680)	(0.150)	(0.129)	(0.0000137)	(0.00000312)	(0.00000112)	(0.00000110)
Scale	1.104	1.205	1.383	1.231	0.373***	0.283***	0.413***	0.265***
	(1.198)	(0.772)	(1.173)	(1.544)	(0.0000320)	(0.0000138)	(0.0000428)	(0.0000222)
G_factor	-1.828	-2.027**	-1.966**	-1.650	-1.211***	-1.089***	-1.176***	-1.124***
	(1.513)	(0.857)	(0.849)	(1.332)	(0.0000333)	(0.0000130)	(0.0000283)	(0.0000235)
T_fdi	-0.118	-0.0149	0.392	0.266	-0.222***	-0.207***	-0.0861***	-0.0836***
	(0.620)	(0.295)	(0.353)	(0.434)	(0.0000358)	(0.0000103)	(0.00000861)	(0.00000653)
T_Rd	1.437***	1.503***	1.420***	1.461***	0.0876***	0.0712***	0.158***	0.134***
	(0.310)	(0.142)	(0.163)	(0.164)	(0.00000777)	(0.00000474)	(0.0000232)	(0.00000879)
_cons	9.813*	6.218***	3.193	1.698	1.675***	1.743***	2.321***	2.948***
	(5.166)	(1.069)	(3.891)	(5.749)	(0.00363)	(0.00638)	(0.00766)	(0.00775)
Industry FE	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES
R-Squared	0.919	0.918	0.903	0.902	0.997	0.997	0.997	0.997
N	45	45	45	45	30	30	30	30

Note: The robust standard errors in parentheses, ***, **, and * indicate significant at the level of 1%, 5%, and 10% respectively.

The first four columns of Table 6 show the estimated results of the impact of forward GVC production length of the high-tech industry on CO_2 emissions, which is negative at a significant level of

5%; The first four columns in Table 7 indicate that the CO_2 emissions of high-tech industries are subsequently reduced as the backward GVC production length is extended. The overall effect of the backward GVC production length on CO_2 emissions is better than the forward GVC production length. The main reason for this phenomenon is that the production of high-tech industries in China's equipment manufacturing industry is mainly to provide high-level intermediate products to other countries. In this process, the level of production increases with deeply participating in GVC activities, and thus makes CO_2 pollution in the production process continues to decrease. Due to the shortage of labor resources and the increase of basic production costs in China, the simple processing and production part of China's equipment manufacturing high-tech industry has begun to move to other developing countries, resulting in a stronger CO_2 emission reduction effect caused by extending the length of backward GVC production length.

The last four columns in Table 6 show that the CO_2 emissions of the medium-tech industry are affected by the extension of the forward GVC production length, that is, for every 1% increase of the forward GVC production length, CO_2 emissions will increase by about 1%. This is because the medium-technology industry in China's equipment manufacturing industry is still dominated by labor-intensive production. In the process of participating in the GVC, it has not completely separated from the low value-added and high CO_2-emission production stage, and the CO_2 emissions level of production is relatively high. The average growth rate of CO_2 emissions from the transportation equipment manufacturing industry in 15 years was 8.36%, the CO_2 emissions increased by 458.57 million tons, and the average annual growth rate of the fabricated metal products industry reached 6.99%. The coefficients of the backward GVC production length related indicators in the last four columns of Table 7 are all positive, indicating that the backward GVC production length also has a driving effect on the increase of CO_2 emissions in the medium-tech industry. The reason is that the medium-tech industry in China's equipment manufacturing industry has a low position in the international division of production. This is because the fabricated metal product industry and transportation equipment manufacturing industry have higher requirements for precision parts, and the core technology manufacturing capabilities of China's equipment manufacturing industry are still weak, the change from basic core components, basic core technology and basic core materials to high-tech, high-end products and high-end components is very slow. China's medium-tech equipment manufacturing industry mainly provides final products to other countries in the form of OEM (Original Equipment Manufacturer). Therefore, the GVC participation mode based on backward linkage will generate more CO_2 .

It is worth noting that the regression results of the high-tech industries are in the same direction as the overall regression results, and will reduce CO_2 emission, but the results of the medium-tech industries are opposite to the overall results. This may be because high-tech industries deepen the participation in the GVC by improving the level of research and development, while the increased participation in the GVC of the medium-tech manufacturing industry is at the expense of producing more resource-intensive products. China is committed to reducing resource-intensive production and encouraging high-tech R&D production activities, so that the CO_2 emission reduction effect of high-tech industries is stronger than the CO_2 promotion effect of medium-tech industries, which in the end will reduce the CO_2 emissions of the whole equipment manufacturing industry.

Conclusions and policy implications

Based on the decomposition framework of the GVC production length and the model of the impact of participating in GVC on CO_2 emissions, this paper derives the core indicators and constructs a STIRPAT model of the impact of participating in GVC on CO_2 emissions, clarifies the specific impact of different GVC participating modes on the CO_2 emissions of the equipment manufacturing industry, and analyzes the industry heterogeneity of this impact. The main conclusions of the study are as follows:

First of all, the extension of the forward production length of the GVC can effectively reduce CO_2 emissions. The extension of the forward simple GVC production length has the best effect, and the forward complex GVC production length has no effect on CO_2 emissions; the CO_2 emission reduction effect of the backward GVC production length and the backward simple GVC production length is significant, which is better than the result of the forward GVC production length, and the extension of the pure foreign GVC production length also has a slight CO_2 emission reduction effect. It shows that the improvement of cleaner production technology in China's equipment manufacturing industry at the current stage mainly stays at the simple production stage of GVC, only reducing CO_2 emissions in the processing and assembly links. Hence, the cleaner production technology of complex GVC production activities needs to be improved urgently.

Secondly, for high-tech industries, the extension of the forward and backward GVC production length will reduce CO_2 emissions; while the extension of the forward and backward GVC production lengths of the medium-tech industry will increase CO_2 emissions. This shows that the level of cleaner production in China's high-tech industries is increasing with the deepening of the participating degree of the GVC; however, the production of the medium-tech industries still relies on basic advantages such as abundant labor resources, and has been locked in the low-end link of the GVC. In addition, the high-tech industry has developed more vigorously, driving the overall CO_2 emission reduction trend of the equipment manufacturing industry to improve. Therefore, China should implement an industry differentiation policy, improve the overall competitiveness of high-tech industries, and promote the realization of qualitative changes in low-tech industries (Chenyao et al. 2020).

Thirdly, policy regulations, factor structure and foreign investment can effectively reduce CO_2 emissions, but the expansion of production scale and R&D investment will increase CO_2 emissions. It shows that, in recent years, China's improvement in environmental regulations, the adjustment of factor structure and the introduction of foreign capital have brought positive CO_2 emission reduction effects, but the problem of high-CO_2 activities in the export intermediates production and inefficient use of R&D funds still exists.

Based on the above conclusions, the following policy implications are proposed:

Firstly, continue to deepen the degree of participating in GVC and move out of low-end production activities. In the context of participating in GVC, the extension of the GVC production length will bring great potential for CO_2 reduction worldwide, especially in manufacturing sector (Rilong et al. 2020). It provides strong evidence for China's unswerving participation in the international division of labor and adherence to opening up. Therefore, China's equipment manufacturing industry should actively respond to the "Belt and Road" initiative, cooperate with countries along the "Belt and Road" in production activities, and undertake more high-value-added, low-CO_2 production activities from developed countries. Transfer low-end production activities to other developing countries where resources and labor are cheaper. After that, China's equipment manufacturing industry can further extend the GVC production length, and be involved in the high-end production link of the GVC totally (Chenyao et al. 2020).

Secondly, maintain the advantages of intermediate production in simple GVC activities and improve the clean production technology level of complex GVC activities. At present, China's equipment manufacturing industry has made great progress in simple GVC production and has reached the requirements of cleaner production, but it still needs to improve the CO_2 emission reduction effect of complex GVC activities. Accordingly, on the one hand, it is necessary to optimize the import quality of intermediate products through learning the manufacturing technology and processing technology of high-tech intermediate products, improve the level of intermediate products exported in complex GVC activities, and extend the GVC production length returning to the exporting countries. On the other hand, to encourage equipment manufacturing enterprises to "go global" means enterprises need to conduct in-depth cooperation with multinational companies in R&D, design, brand building, etc., seek new path of participating in GVC with technological innovation to get out of the dilemma of "low-end lock-in" and extend the length of pure foreign GVC production length.

Thirdly, keep the clean production advantages of high-tech industries, accelerate the transformation and upgrading of medium-tech industries, and enable the equipment manufacturing industry to achieve the CO_2 emissions reduction of the entire industry. For high-tech industries, while vigilant against the implementation of restrictions by countries with high-income, we should strive to achieve more advanced technological breakthroughs, seize the strategic position of high-end production links, and steadily move to the top of the GVC. The medium-tech industry needs to expand the production scale of high value-added intermediate products through the extensive introduction of advanced low-CO_2 production technologies, reduce dependence on the export of pollution-intensive intermediate products, and gradually transform from the high-CO_2 GVC participation channels to high-tech channels. By this way, the entire equipment manufacturing industry will achieve CO_2 emission reductions eventually.

Last but not least, continue to strengthen environmental control and foreign investment, improve the factor structure and R&D expenditure utilization. (1) Environmental regulations have a guiding role in solving environmental problems. China should gradually raise the threshold of environmental control and improve the environmental pollution legal system. (2) The introduction of foreign capital has clearly helped the equipment manufacturing industry to upgrade clean technologies. China should continue to optimize its business environment and attract foreign investment in high-end technology industries. (3) The current factor structure of China's equipment manufacturing industry is still resource-oriented, and the CO_2 emission increase effect of the expansion of production scale is obvious. The factor structure can be transformed to technology-intensive by increasing the skilled labor and R&D personnel. (4) The government need to strictly supervise the destination of R&D expenditures, allocate R&D expenditures reasonably, guide enterprises to use R&D expenditures efficiently, and promote enterprises to increase investment in independent innovation, so that the enterprises of equipment manufacturing industry could climb to the higher level of participating in GVC through its own capabilities.

Declarations

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Availability of data and materials The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Competing interests The authors declare no conflict of interest.

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Figures

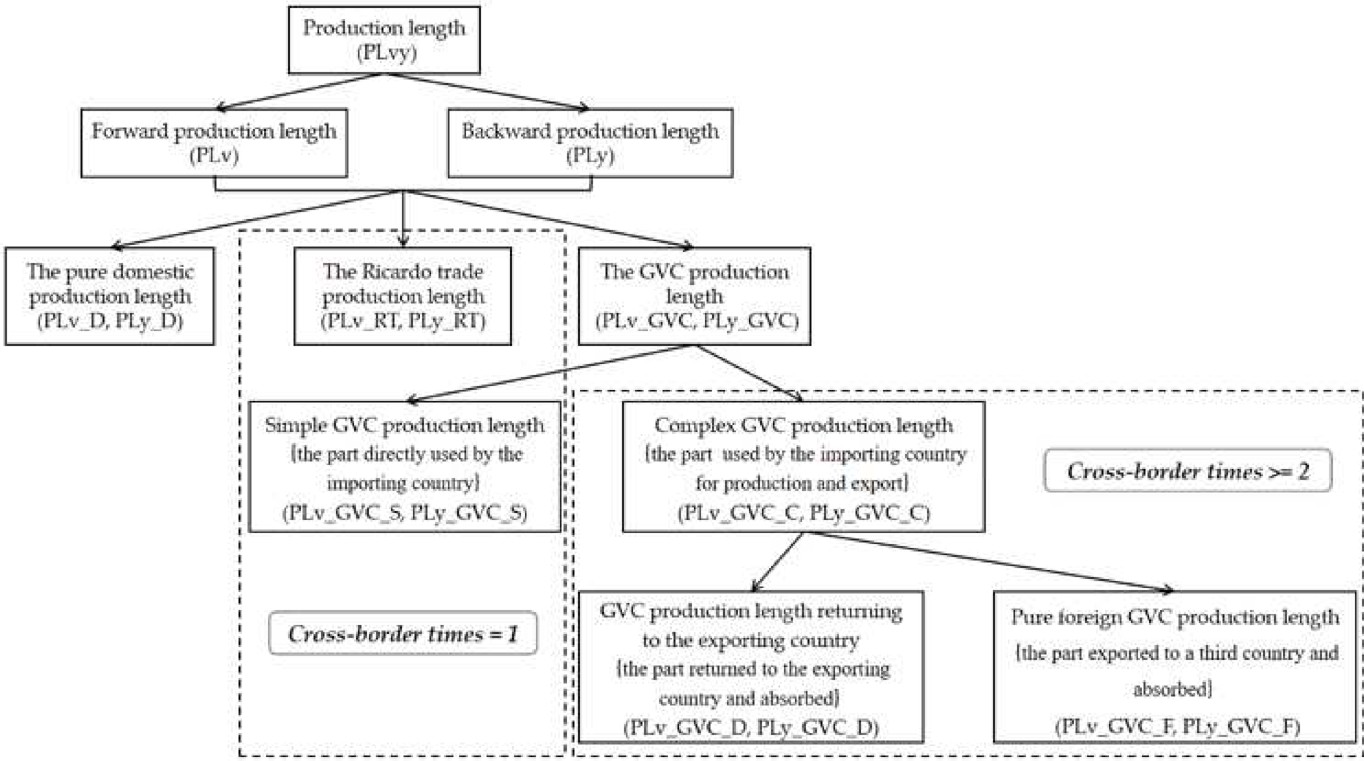

Figure 1

The decomposition model of production length

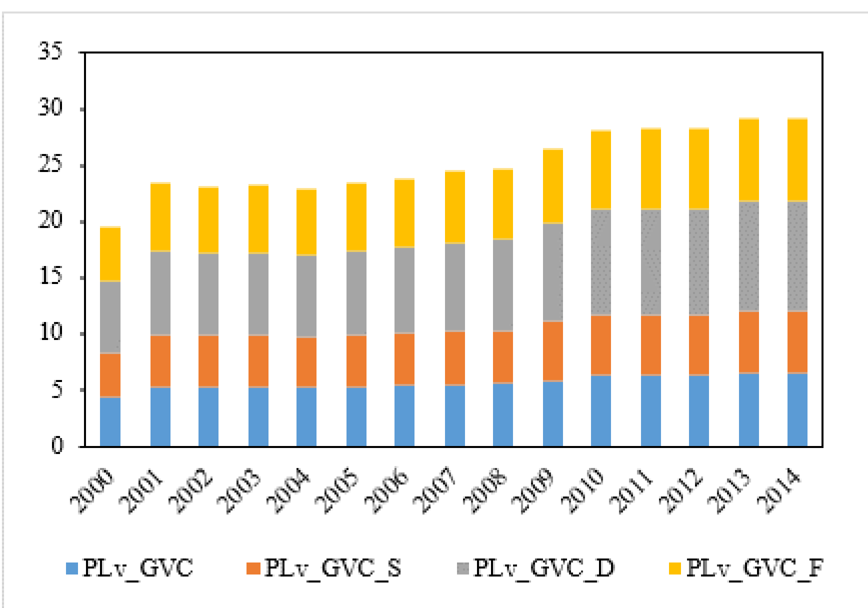

Figure 2

The forward GVC production length of China's equipment manufacturing industry

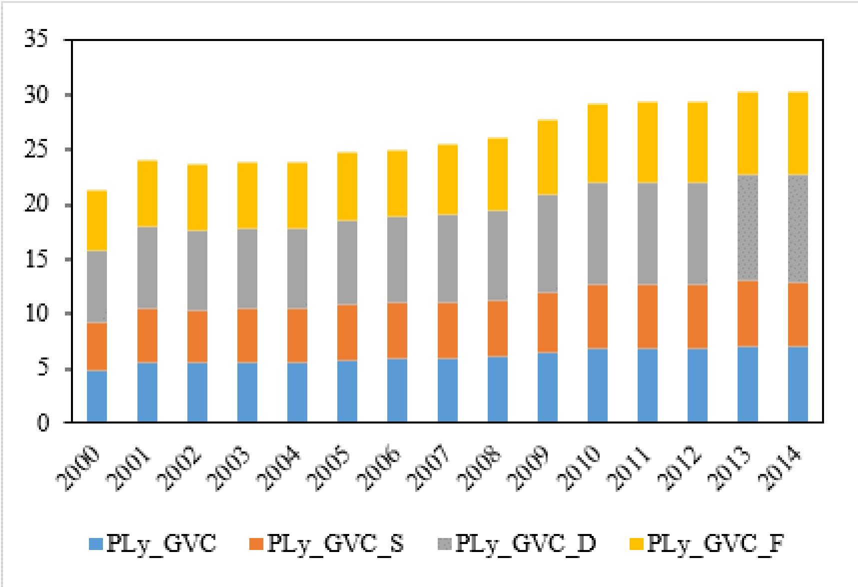

Figure 3

The backward GVC production length of China's equipment manufacturing industry

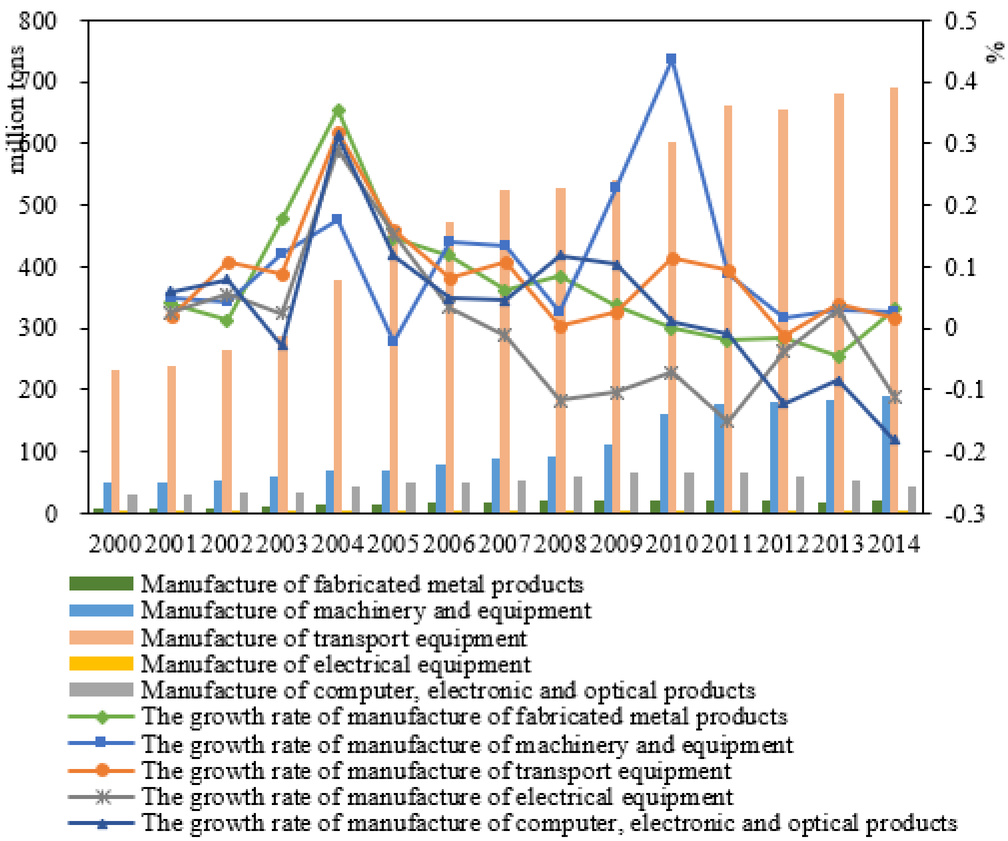

Figure 4

The CO_2 emission of China's equipment manufacturing industry from 2000 to 2014