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The Impact of Manufacturing Digitization on Embodied Carbon Intensity: A Global Value Chain Perspective

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Abstract. Climate issues have become one of the most important topics for the sustainable development of the global economy. Balancing trade gains with carbon emissions has become a strategic objective for each economy. Based on cross-country panel data from 2006-2018, this essay comprehends the relationship between manufacturing digitization and export embodied carbon intensity at the theoretical level and tests the theoretical arguments using panel models. In addition, the findings show that the digitization of manufacturing can reduce the export embodied carbon intensity through two paths: the deepening of the forward embeddedness and the improvement of the division of labor position in GVCs.

Keywords: Digitization; Export Embodied Carbon; The Forward Embeddedness; The Division of Labor Position.

1. Introduction

The manufacturing sector has a huge potential to reduce carbon emissions. In the context of the international division of labor, the achievement of carbon emission reduction targets should not be focused solely on domestic demand, the impact of foreign demand on domestic carbon emissions also needs to be given attention. According to the World Economic Forum, by 2030, the amount of carbon emissions that industries can derive from the development of ICT is expected to reach 12.1 billion tonnes. Therefore, the power of digital technology can be leveraged to better reconcile the relationship between export trade profits and carbon emissions in traditional manufacturing industries.

According to the existing literature, the development of the real and digital economy has been a hot topic of academic research. The digitization of the manufacturing industry, on the one hand, can enhance technological innovation[1], control costs, reduce labor consumption, and enhance enterprise total factor productivity[2]; on the other hand, it can enhance green innovation and performance[3,4], and reduce carbon emissions [5]. As for embodied carbon, high carbon emission intensity, growth in the scale of domestic final demand, trade surplus, and processing trade are currently considered to be the main reasons for the increase in embodied carbon[6,7,8].

There are fewer studies on digitization and export embodied carbon in manufacturing. Therefore, this essay uses a sample of 57 economies' panel data to demonstrate and test the relationship of two variables, providing arguments for a better balance between trade gains and carbon emission reduction under the international division of labor.

2. Research Hypotheses

2.1. Digitization of Manufacturing and Export Embodied Carbon Intensity

In the digital age, the manufacturing industry can leave repetitive tasks to AI, aggregating the workforce into higher-end production activities. Through the input of information and data elements, it is possible to obtain a better input-output ratio, the transmission and sharing of data also can improve the efficiency of collaboration in various departments, reducing the additional costs and inefficiencies brought about by asymmetry. In addition, digital technology has a spillover effect, which is conducive to the enhancement of innovation skills, and based on the data platform it can more accurately and quickly control the direction of the international market, and enhance the competitiveness of product exports. In terms of embodied carbon emissions, the application of modern information technology has changed the production operation mode of the traditional manufacturing industry, which is conducive to breaking down the upstream and downstream barriers, promoting the research and development of green technology among enterprises, and ultimately reducing energy consumption and carbon emissions. Based on this, H1 was proposed:

H1: Digitization of manufacturing can reduce the embodied carbon intensity of exports.

2.2. Impact Path Analysis on Global Value Chains

Digital technology reduces trade costs such as transport costs and tariff barriers. Moreover, efficient and cleaner equipment improves resource and energy utilization, thus enabling a country's manufacturing sector to deepen its forward embeddedness in GVCs. The digitization of manufacturing in the international division of labor can reduce the share of trade profits from low value-added products by reducing the participation in resource-consuming and low-end processing production. With the deepening of GVC's forward embedding, its own production technology, resource allocation and management structure are continuously optimized and iterated, so that the company can have more abundant capital to invest in core clean technology research and development, forming a virtuous cycle. Based on this, H2 was proposed:

H2: The digitization of manufacturing can reduce the embodied carbon intensity of exports by deepening the forward embeddedness of GVCs.

Digital technology overcomes time and space constraints, reduces transaction and search costs, and the growth in the scale of exports brings higher export value added. Besides, digital technologies are driving enterprises towards intelligence, investing more human and financial resources in R&D and innovation, making the production process less dependent on traditional energy sources, and enabling enterprises to shift to higher value-added production segments in the division of labor, thereby enhancing the global value chain position. Countries in the relative downstream of GVCs are mainly engaged in low value-added production jobs and are more dependent on traditional resources, resulting in higher embodied carbon intensity of exports. Based on this, H3 was proposed:

H3: The digitization of manufacturing can reduce the embodied carbon intensity of exports by increasing division of labor positions in GVCs.

3. Methodology and Data

3.1. Description of the Model

To examine the impact of manufacturing industry digitization on export embodied carbon intensity, a benchmark regression model is constructed as follows:

$$LnCEI_{ijt} = \alpha_0 + \alpha_1 dig_{ijt} + \alpha_2 Controls_{it} + \emptyset_i + \emptyset_j + \emptyset_t + \varepsilon_{ijt} \quad (1)$$

Where i, j, t are the economy, industry, and year, respectively. $LnCEI$ is the export embodied carbon intensity, and dig is the degree of digitization of the manufacturing sector. $Controls$ are control variables, $\emptyset_i$, $\emptyset_j$,$\emptyset_t$,ε_{ijt} are economy, industry and year fixed effects as well as random error terms.

To examine the two influence paths, the mediation model is constructed as follows:

$$M_{ijt} = \beta_0 + \beta_1 Lndig_{ijt} + \beta_2 Controls_{it} + \emptyset_i + \emptyset_j + \emptyset_t + \varepsilon_{ijt} \quad (2)$$

$$LnCEI_{ijt} = \gamma_0 + \gamma_1 dig_{ijt} + \gamma_2 M_{ijt} + \gamma_3 Controls_{it} + \emptyset_i + \emptyset_j + \emptyset_t + \varepsilon_{ijt} \quad (3)$$

Where M_{ijt} denotes the mediating variables, including the forward embeddedness and the improvement of the division of labor position. β, γ are the parameters to be estimated.

3.2. Description of Variables

(1) Core explanatory variable: export embodied carbon intensity ($LnCEI_{ijt}$). This indicator shows the carbon intensity of total exports from industry j in exporting country i to importing partner countries, including carbon emissions from domestic and foreign industries upstream in the production chain.

(2) Core explanatory variable: the degree of manufacturing digitization (dig_{ijt}). Referring to existing literature methods[9], it is measured in terms of digitization inputs as well as the level of national digital economy development. The formula is as follows:

$$dig_{ijt} = Input_{ijt} \times Digital_{it}$$

Where $Input_{ijt}$ represents the level of industry digitization input, that is, the proportion of the manufacturing industry's input in the digital industry of each economy. $Digital_{it}$ represents the level of development of digital economy in each economy, we constructed the index system of the level of development of digital economy (Table 1), and used the entropy value method to calculate the development of digital economy in each economy.

Table 1. Indicator system for the level of development of the digital economy

Level 1 indicator	Level 2 indicators	Level 3 indicators	Source of data
the development of the digital economy	Digital infrastructure	Fixed broadband subscriptions	WDI
		Mobile cellular mobile subscription rate	WDI
		Secure Internet server coverage	WDI
	digital technology innovation environment	Research and development expenditure	WDI
		Tertiary enrolment	WDI
		Intellectual property protection strength	WEF
	national digital competitive intensity	ICT goods exports	WDI
		ICT services exports	WDI
		Information Communication Technology exports	WDI

(3) Mediating variables.

The Global Value Chain Forward Embeddedness (GVC_PF) is calculated as follows:

$$\text{GVC\_PF} = \frac{V\_GVC_s^i}{V_s^i} \tag{4}$$

Where $V\_GVC_s^i$ denotes the value added of intermediate goods exported by industry sector i in country s for use in the production of final goods in each country, and V_s^i denotes the sum of the forward value-added decompositions of industry sector i in country s.

By comparing the length of production of forward and backward linkages of a country or industry sector in a GVC, the GVC location index is used to measure the position of this country or industry sector in the GVC[11], which is calculated by the following formula:

$$GVC\_P_s^i = \frac{Plv\_GVC_s^i}{Ply\_GVC_s^i} \tag{5}$$

Where $Plv\_GVC_s^i$ denotes the GVC production length for countries and regions based on forward linkages, while $Ply\_GVC_s^i$ denotes the GVC production for countries and regions based on backward linkages Length.

(4) Control variables. The following variables are controlled in the empirical evidence to reduce errors arising from endogeneity or omission of variables, including Economic development(*gdp*), capital level(*cap*), foreign direct investment(*fdi*) and urbanization level(*urb*).

3.3. Source of Data

The empirical data covers 17 manufacturing industries (17 manufacturing industries: D10T12 food, beverages, and tobacco; D13T15 textiles, textiles, leather, and footwear; D16 wood and wood and cork products; D17T18 paper products and printing; D19 coke and refined petroleum products; D20 chemical products; D21 drugs, pharmaceutical chemicals, and plant products; D22 rubber and plastic products; D23 other nonmetallic mineral products; D24 base metals; D25 fabricated metal products; D26 computer, electronic and optical equipment; D27 electrical equipment machinery and equipment, nec; D29 petroleum products; D20 chemical products; D21 drugs, pharmaceutical chemicals, and plant products; D22 rubber and plastic products; D23 other nonmetallic mineral products; D24 base metals; D25 fabricated metal products; D26 computer, electronic and optical equipment; D27 electrical equipment machinery and equipment, nec;D28 Machinery and equipment; D29 motor vehicles, trailers and semi-trailers; D30 other transportation equipment; D31T33 manufacturing nec; repair and installation of machinery and equipment.) in 57 economies(58 economies: China, Saudi Arabia, Argentina, Australia, Austria, Belgium, Bulgaria, Brazil, Canada, Switzerland, Colombia, Costa Rica, Czech Republic, Germany, Denmark, Estonia, Finland, France, United Kingdom, Greece, Hong Kong, China, Croatia, Hungary, Indonesia, India, Ireland, Iceland, Israel, Italy, Japan Kazakhstan, Cambodia, Korea, Laos, Lithuania, Luxembourg, Latvia, Malta, Myanmar, Malaysia, Netherlands, Norway, New Zealand, Peru, Philippines, Poland, Portugal, Romania, Singapore, Slovakia, Slovenia, Sweden, Thailand, Tunisia, USA, Vietnam, South Africa.), spanning the period 2006-2018. The data used are from OECD's ICIO tables, TiVA database, TECO2 database, WDI, World Economic Forum, and UIBE GVC Index database.

4. Analysis of Empirical Results

Table 2. Full sample regression results

	(1)	(2)	(3)	(4)	(5)
dig	-1.112***	-1.125***	-1.143***	-1.145***	-1.104***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
urb		-0.062	-0.090	-0.087	-0.061
		[0.335]	[0.163]	[0.180]	[0.383]
fdi			0.011***	0.011***	0.011***
			[0.000]	[0.000]	[0.000]
gdp				0.003	0.005**
				[0.186]	[0.019]
cap					-0.059***
					[0.000]
_cons	6.140***	6.403***	6.521***	6.507***	6.568***
	[0.000]	[0.000]	[0.000]	[0.000]	[0.000]
N	12522	12522	12522	12522	12269
adj. R-sq	0.947	0.947	0.947	0.947	0.949
Economic fixed effects	YES	YES	YES	YES	YES
Year fixed effects	YES	YES	YES	YES	YES
industry fixed effect	YES	YES	YES	YES	YES

p-values in brackets

*** p < 0.1, ** p < 0.05, *** p < 0.01**

Table 2 reports the results of the H1 test. After controlling for year and industry fixed effects and adding control variables one by one, it can be seen that the regression coefficient is significantly negative at the 1% level, indicating that the digitization of the manufacturing industry can reduce the intensity of exported embodied carbon emissions, verifying H1.

To demonstrate the robustness of the results, we successively treated the data extremes, replaced the core variables, and replaced the test model treatment. To avoid bidirectional causality between variables, the explanatory variables are regressed with a one-period lag. The above regression results are all robust, proving once again that the estimation results are reliable.

Columns (1) to (2) of Table 3 report the results of the tests on the forward embeddedness effect of GVCs. The empirical results show that the digitization of manufacturing can increase the forward embeddedness of GVCs at the 1 percent level, thus further reducing the export embodied carbon intensity, validating H2. The digitization of the manufacturing industry can improve industrial efficiency, release more manpower and capital to invest in clean research and development, and with the deepening of forward participation in the GVC, it can continuously learn from advanced countries' technologies and production operation and management styles, and continuously optimized and iterated.

Columns (3) to (4) of Table 3 report the results of the GVC division of labor position test. The results show that the digitization of the manufacturing sector can significantly increase its GVC division of labor position index at the 1% level, which in turn reduces the intensity of export embodied carbon, validating H3. As the position in the global value chain improves, enterprises are engaging more in high value-added, low-pollution research and development and other production processes, changing the structure of export and reducing the embodied carbon intensity of exports.

Table 3. Regression results of global value chain impact mechanisms

	(1)	(2)	(3)	(4)
dig	0.493***	-0.985***	0.239***	-0.708***
	[0.000]	[0.000]	[0.000]	[0.002]
GVC_PF		-0.243***		
		[0.001]		
$GVC\_Position$				-1.680***
				[0.000]
_cons	0.582***	6.711***	-0.225***	6.205***
	[0.000]	[0.000]	[0.000]	[0.000]
N	12342	12269	12342	12269
adj. R-sq	0.944	0.949	0.936	0.950

p-values in brackets

*** p < 0.1, ** p < 0.05, *** p < 0.01**

5. Main Conclusion and Recommendations

As discussed above, it is found that digitization of manufacturing significantly reduces the export embodied carbon intensity of the manufacturing sector and that this finding is highly robust. In addition, the digitization of manufacturing can reduce the embodied carbon intensity of exports by deepening of the forward embeddedness and the improving of the division of labor position in GVCs.

Accordingly, the following recommendations are made: (1) Seizing the opportunities of digitization change, attaching importance to the close integration of manufacturing and digital technology, and promoting the development of a green economy. All countries are interconnected and interdependent.

Carbon reduction targets in the Paris Agreement need to be accomplished through the concerted efforts of all countries. (2) Enterprises need to accelerate the upgrading of cleaning equipment and technology, and monitor and supervise carbon emissions in the production process in real time. (3) It is necessary to increase investment in R&D, pay more attention to the quality of export products, break through the predicament of "low-end lock-in", deepen the degree of forward embeddedness in GVCs, improve the status of the division of labor in GVCs, and form a green and low-carbon production chain, so that we can obtain trade gains and reduce environmental costs at the same time.

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