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CAN MANUFACTURING OUTPUT SERVITIZATION REDUCE CARBON EMISSIONS?

Hongsen Wang[1,] * and Dongni He[2]

[1]School of Business Administration
Northeastern University
Shenyang, China
*Corresponding author's e-mail: 1810423@stu.neu.edu.cn

[2]The Guangzhou Institute of GBA
Guangzhou, China

Carbon emissions from manufacturing have been a growing global concern in recent years. The growth in manufacturing firms' service output and its carbon emission reduction effect have received less attention, though. Using data from 2008-2020 for listed companies in China, this study empirically analyzed the effects of manufacturing output servitization on carbon intensity. The results revealed a significant negative relationship between them. Heterogeneity analysis finds that the carbon emission reduction effect of manufacturing servitization is strongest in (i) private and relatively small-scale firms and (ii) developed regions and capital-intensive industries. The mediating effect study shows that green TFP and revenue growth rate are the transmission channels for the environmental impact of manufacturing servitization. This study verifies that servitization is a feasible path to coordinate high-quality economic development with resource and environmental constraints from different perspectives to provide a reference for the realistic development of diverse economies.

Keywords: Manufacturing Servitization; Carbon Intensity; Industrial Transformation.

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1. INTRODUCTION

The manufacturing industry is one of the pillars of the national economy and an important foundation for improving the competitiveness and resilience of the economy. Servitization of manufacturing is a competitive strategy adopted by enterprises to achieve product differentiation, enhancement of customer experience and loyalty, and organizational restructuring (Pelli and Lahtinen, 2020), ultimately leading enterprises to improve their capabilities, competitiveness, and profitability (Manresa *et al*., 2021). There are two aspects of manufacturing servitization: input servitization and output servitization, which respectively means that services occupy an increasingly important position in the total input and output of manufacturing. In recent years, subscription services, after-sales services, scrap or recycling of physical products, and other service links have played an increasing role in the manufacturing value chain; therefore, output servitization has become one of the development directions of manufacturing enterprises in the world. External services related to goods are becoming increasingly complex and important to customers (Ullah *et al*., 2022). As an output of intangible components, services increase the value and sales of goods. For example, Apple's service business constitutes a significant part of its revenue. According to Apple's performance statement for the Fourth quarter of 2022, services accounted for 21.28% of total net sales, second only to the iPhone, and are growing rapidly. Another example is that by changing its operation model and expanding services such as engine maintenance, engine leasing, and engine data analysis and management, Rolls-Royce has increased its service-oriented revenue by binding users with service contracts. In the face of the global economic transformation from material consumption to service and experience consumption, the servitization of manufacturing output has a positive impact on tapping economic productivity and growth potential.

Increasing environmental degradation and the unsustainability of economic growth have attracted a large number of studies on how manufacturing can reduce polluting emissions and improve environmental efficiency (Wang *et al*., 2021). Advanced economies have generally experienced manufacturing servitization, demonstrating that service-oriented transformation has obvious advantages in reconciling economic and environmental sustainability (Mont, 2002). Relevant studies have focused on the service input of manufacturing (Hao *et al*., 2022; Zhao and Chen, 2021; Tang *et al*., 2022) rather than on the service output. The output servitization strategy can contribute equally to reducing resource consumption and environmental pollution by providing relatively "clean" service products. As an increasing number of countries and regions

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impose carbon restraints on economic development, the contradiction between the development of the traditional manufacturing industry and the tightening of environmental regulations has become prominent. As an emerging model of the integration of the manufacturing and service industries, it is important to study whether manufacturing output servitization is conducive to the transformation to advanced low-carbon development. China's (the largest manufacturer) share in the value-added of global manufacturing rose from 18.2% in 2010 to 29.8% in 2021. In addition, China's manufacturing industry has a high degree of participation in the global industrial chain and is undergoing a period of transformation. Taking China's manufacturing enterprises as an example, this study examines the carbon emission reduction effect of output servitization, which holds significance as a reference point for countries to build an environment-friendly manufacturing industry.

2. LITERATURE REVIEW

With the development of service, the division of labor, integration, and coordination among industries has consistently improved (Reiskin *et al*., 2000). In recent decades, many advanced manufacturing enterprises worldwide, such as Hewlett-Packard, Michelin, and Nokia, have begun to combine specialization in both "manufacturing and service." "Manufacturing + service" is a new servitization model based on the integration of production-oriented manufacturing economy and consumption-oriented service economy (Wang and Zhang, 2019). Service-oriented transformation has gradually become the outcome of manufacturing upgrading (Gao and Yuan, 2020). With the increasing necessity of service as an input in the production process or the increasing proportion of service products in the output (Li *et al*., 2020a, b), the transformation of manufacturing enterprises has gradually resulted in servitization gaining popularity (Gao and Yuan, 2020). Many scholars have studied the input servitization of manufacturing (Liu *et al*., 2020), mainly focusing on economic benefits. For example, manufacturing servitization helps optimize the efficiency of resource allocation (Grossman and Rossi-Hansberg, 2008; Liu *et al.*, 2010), improve the supply and value chains of enterprises (Liu *et al.*, 2010; Xu *et al.*, 2017), improve innovation capabilities and productivity (Li, 2020), and promote the transformation of the industrial structure (Zhou, 2013). Since the proportion of value-added is higher in services than in tangible production (Paschou *et al*., 2020), output servitization is also an important means of upgrading the manufacturing value chain. Therefore, this study focuses on output servitization. The so-called manufacturing output servitization is that with technological progress and intensified market competition, manufacturing enterprises are increasingly extending from the original focus on the supply of physical products to derivative services, thereby becoming "product + service" suppliers in order to meet the increasingly diversified and personalized needs of consumers and customers (Chen and Shen, 2019). The services involved in this process include after-sales services, customized services, solutions, product recycling, and management consulting. In the context of low-carbon actions, manufacturing enterprises may not be able to rely on expanding resource consumption and market share to guarantee sustained profitability. Additional service activities in the manufacturing sector have the potential to promote value growth (Vandermerwe and Rada, 1988).

Research on carbon emission reduction in manufacturing has primarily focused on the decomposition of carbon emissions and the analysis of its influential factors. Considering only total carbon emissions, most experts believe that the main factors affecting their reduction are energy intensity, energy structure, and economic growth (Wang *et al.*, 2015). Considering economic growth, researchers have found that efficiency and structural optimization may be key factors in reducing carbon emissions (Pan *et al.*, 2011; Shao *et al.*, 2017), both of which depend on technological progress. Technological progress can support the coordinated development of the environment and economy by supporting industrial transformation (Zhu *et al.*, 2014). Felder and Rutherford (1993), Hertwich and Peters (2009), Fischer and Fox (2011), Kanemoto *et al*. (2014) and Zhao *et al*. (2020) believe that developed countries could encourage high-pollution and low-value-added industries to move to developing countries, thus forming spatial transfer of environmental costs. This positive selection of production stages promotes the cross-space coordination of economic and environmental benefits and optimizes the overall layout of the industrial structure (Lv *et al*., 2021). But it also has the potential to create carbon leakage and carbon shifting. According to the environmental Kuznets curve, the environmental conditions of regions receiving industrial transfer may initially experience deterioration, followed by gradual improvement (Dinda, 2004). But developed countries may monopolize technology, standards, and software, locking developing regions at the lower end of the value chain, resulting in a double imbalance in economic development and carbon emissions.

In recent years, researchers have studied the environmental impact of manufacturing servitization. For example, when Ventura *et al*. (2020) used inspection and maintenance as a type of after-sales service for in-service vehicles, they found that the levels of carbon monoxide and hydrocarbons in vehicles lacking maintenance were up to five times that of serviced vehicles. Manufacturing services also contribute to eco-economic sustainability by improving product performance and extending the life cycle of manufactured goods (Fernando *et al.,* 2020). Another example is the energy saving caused by the optimization of manufacturing supply chain logistics (Jazairy, 2020) and the air pollution control brought about by the inspection and maintenance program (Ventura *et al*., 2020). This does not entirely imply that manufacturing services reduce carbon emissions. Although service goods tend to be intangible and immaterial, as intermediaries of late-mover linkages, their provision requires many upstream material goods and energy, thus indirectly increasing resource or energy consumption and pollution emissions of the upstream non-service sector (Song *et al*., 2020a). Under the accounting framework of embodied carbon emissions, Hou *et al*. (2021) demonstrated that the industry scale and carbon intensity of the upstream industry led to sharp growth in embodied carbon emissions in the service industry. In addition, even green enterprises may not sufficiently address environmental impact when providing service goods, which may eventually lead to a service input paradox (Kamal *et al*., 2020), and the lack of consumer awareness inadvertently increases the environmental impact of service production and consumption (Xiong and Wang, 2020). In summary, manufacturing servitization has both positive and negative effects on carbon emissions. However, empirically, manufacturing servitization, overall, helps alleviate the contradiction between economic growth and environmental protection (Rothenberg, 2007; Zhu *et al*., 2020; Wang *et al*., 2018; Rao, 2013) and promotes green and low-carbon development.

A review of the existing literature revealed that most research uses (i) the macroeconomic data of the regional and industrial input-output table to demonstrate the environmental effect of manufacturing input servitization or (ii) management methods to focus on a specific service function at the enterprise level to evaluate the effect of servitization on the energy efficiency or pollution emission intensity of manufacturing enterprises (Li *et al*., 2020a, b). In contrast to being limited to the overall service input or the single service function of enterprises, this study (i) mainly discusses the impact of output servitization of manufacturing enterprises on carbon intensity at the meso-economic level; (ii) examines the heterogeneous impact of servitization on carbon intensity in different regions, industries, and enterprises; and (iii) analyzes the mediating effect, theoretically and empirically. The purpose of this study is to provide a useful supplement to research on low-carbon transformations of manufacturing enterprises and a reference for formulating precise carbon policies for the public sector.

3. MECHANISM ANALYSIS

In a traditional economic model, profit acquisition and value creation inevitably lead to resource consumption. Service elements have many environmental protection characteristics, such as low pollution, low consumption, knowledge intensity, and high output. By enhancing service elements in products, manufacturing enterprises can reduce direct or indirect energy consumption while obtaining profits, thus providing more potential for carbon emission reduction. Based on the previous analysis, **Hypothesis 1** is proposed to test the emission reduction effect of output servitization.

Hypothesis 1: Manufacturing servitization reduces carbon intensity.

Science and technology play vital roles in energy conservation and emission reduction (Song *et al*., 2020b). Based on a service-oriented economy, the industrial manufacturing system and mode, characterized by green, intelligence, and personalization, have become important carriers of technological innovation at this stage (Bustinza *et al*., 2022).

First, manufacturing servitization significantly shortens the spatial and geographical distance between different sectors in the traditional concept, facilitates communication between sectors, and is especially conducive to the exchange of new ideas, patents, and technologies, thereby facilitating innovation in production technology. Second, the reintegration of organizational and business models is the basis of technological innovation. Manufacturing servitization helps enhance the drive for enterprise innovation. The combination of service elements and production links is the result of innovation in traditional structures, production paradigms, and industrial systems. This advanced new model has developed many service-focused low-carbon businesses, promoted high-end, green transformation of the manufacturing industry, and reduced emission intensity. Third, through servitization transformation, enterprises have greatly improved the precise management of customer demand, effectively meeting the personalized needs of consumers. This is conducive to reducing resource waste caused by "ineffective inventory," thereby improving management efficiency. In addition, it indirectly promotes technological innovation in other sectors through technology spillovers, expands the scope of technological benefits, and improves the carbon technology efficiency of enterprises and even the whole industry. Especially for the industries with large total carbon emissions and relatively prominent technology spillover effects, these industries, as the breakthrough fields of carbon technology upgrading, can cause a wider range of "demonstration effect" and "saving effect," which can effectively reduce carbon intensity in the long run.

Therefore, with the continuous improvement of manufacturing servitization, the service undertakes the task of coordinating the links of the product value chain in the whole process, which plays a significant role in improving enterprise efficiency. The servitization of manufacturing output can reduce material consumption by improving output efficiency and alleviating the impact of enterprise economic activities on the ecological environment. **Hypothesis 2** is proposed to further verify the technological innovation effect of servitization transformation on carbon intensity.

Hypothesis 2: Manufacturing servitization reduces carbon intensity through technological innovation effects.

During the stage of extensive growth with low added value, manufacturing companies mainly rely on the production scale to achieve expansion in revenue, which leads to chronically high energy consumption (Lu *et al.*, 2018). Consequently, enterprises may need to improve their value chains to achieve low-carbon growth.

Through the implementation of output servitization, manufacturing enterprises optimize product systems and provide supporting technical support, significantly improving the competitive advantage of products in the market. First, manufacturing enterprises promote personalized customization and provide integrated solutions, significantly increasing the added value of products that meet customers' personalized requirements. Second, servitization of manufacturing output can enhance awareness about manufacturers and their products in the market, improve competitiveness, and ensure higher product price and quality. Third, production fragmentation increases the types of services and strengthens the relationship between services and manufacturing, whereby the embeddedness of services can effectively reduce manufacturing costs (Zhou *et al.*, 2020). In addition, manufacturing enterprises have supported the servitization of products, such as intelligent product technical support, cloud platform construction, and technical training of operation personnel, which further improves the added value of products. As a result, the comprehensive competitiveness and pricing power of manufacturing products in the market has improved significantly.

In summary, owing to the need for low-carbon economic development, the service output link at the end of the "smile curve" will receive more attention at each stage of the manufacturing industry. Based on the above discussion, **Hypothesis 3** is proposed to verify the mediating role of value-added in the relationship between servitization and carbon emission reduction in manufacturing; the correlation path analysis is shown in Figure 1.

Hypothesis 3: Manufacturing servitization reduces carbon intensity through value-added effects.

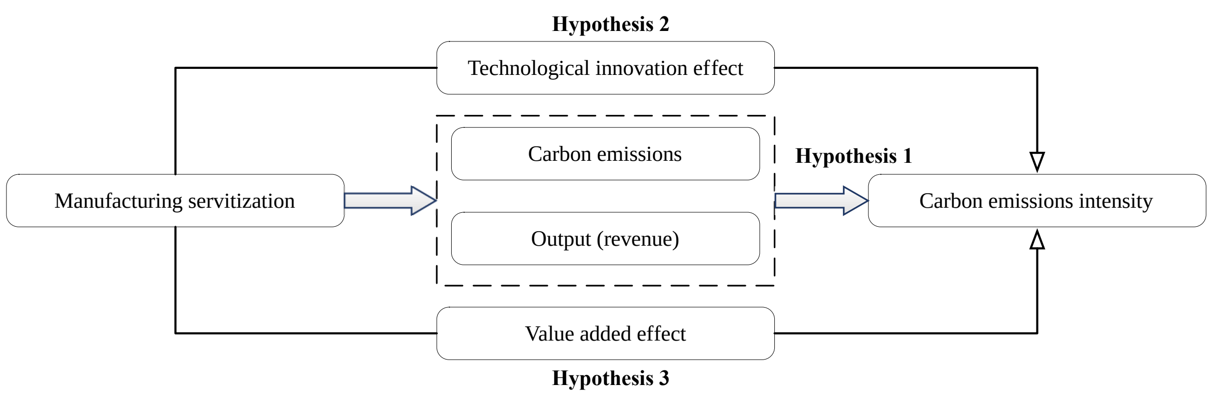

Figure 1. Conduction Path Analysis

The magnitude of carbon intensity (the amount of carbon emitted per unit of output) depends on the contrast between the output forces and carbon emissions. Although the carbon emissions of manufacturing servitization have a significant mitigation effect under most action mechanisms, in some of them, it may also stimulate the generation of carbon emissions. The final effect of manufacturing servitization on carbon intensity depends on a comprehensive game of multiple action mechanisms. The actual impact of manufacturing servitization on carbon intensity needs to be verified through empirical research in different regions, industries, or enterprises. Thus, **Hypothesis 4** was proposed.

Hypothesis 4: The inhibitory effect of manufacturing output servitization on carbon intensity is heterogeneous among regions, industries, and enterprises.

4. MODEL SETTING AND DATA PROCESSING

4.1 Model setting

4.1.1 Explanation of data sources

Based on the previous analysis, the following ordinary least squares regression econometric model was designed:

$$Cei_{it} = \alpha_0 + \alpha_1 Service_{it} + \alpha_2 Control_{it} + \mu_i + \mu_t + \varepsilon_{it}. \tag{5}$$

In Eq. (5), subscripts i and t represent the company and year, respectively. Cei represents the carbon intensity, α are the parameters to be estimated, $Service$ represents the servitization of manufacturing, $Control$ are the controlled variables, μ_i and μ_t are the fixed effects of the company and year, respectively, and ε_{it} is a random error term.

4.1.2 Explanatory variable: servitization of manufacturing ($Service$)

This study screened the sample based on the "business scope" expression of listed manufacturing companies according to whether it clearly indicated that the business of enterprises included the service industry. For example, the primary business of a listed manufacturing enterprise involves the production and sales of automobile engines and their parts and castings, as well as automobile repair, mechanical processing, and technical consulting services. This expression clearly reflects that the enterprise provides some services along with product manufacturing, which is a typical "production + service" example. Simultaneously, we further checked the annual reports of the listed companies, verifying the business description to determine whether they were involved in the service industry. As mentioned above, if the other projects (apart from the primary product manufacturing business) of sample enterprises are predominantly part of the service industry, the income of the non-primary business can be considered as the income of the service under normal circumstances; the proportion of non-operating revenue of the enterprise is used to approximate the output servitization level of the manufacturing.

4.1.3 Explained variable: carbon intensity (Cei)

Carbon intensity is expressed as the ratio of a company's carbon emissions to its revenue, considering both economic growth and ecological protection. Carbon emission data are not required to be disclosed and cannot be found directly. Some databases calculate carbon emissions through the consumption of various types of energy, but energy consumption data at the enterprise level are also difficult to obtain. The China Stock Market & Accounting Research Database (CSMAR) used in this study compiles and summarizes the carbon emission and carbon emission reduction information at the level of listed companies by collecting and sorting the sustainable development, social responsibility, and annual reports of Chinese listed companies. Although the number in the sample is limited, this method attempts to ensure accuracy, authority, and stability.

Figure 2 shows a similar distribution between manufacturing servitization and carbon intensity. This indicates that there may be a connection between explanatory and explained variables.

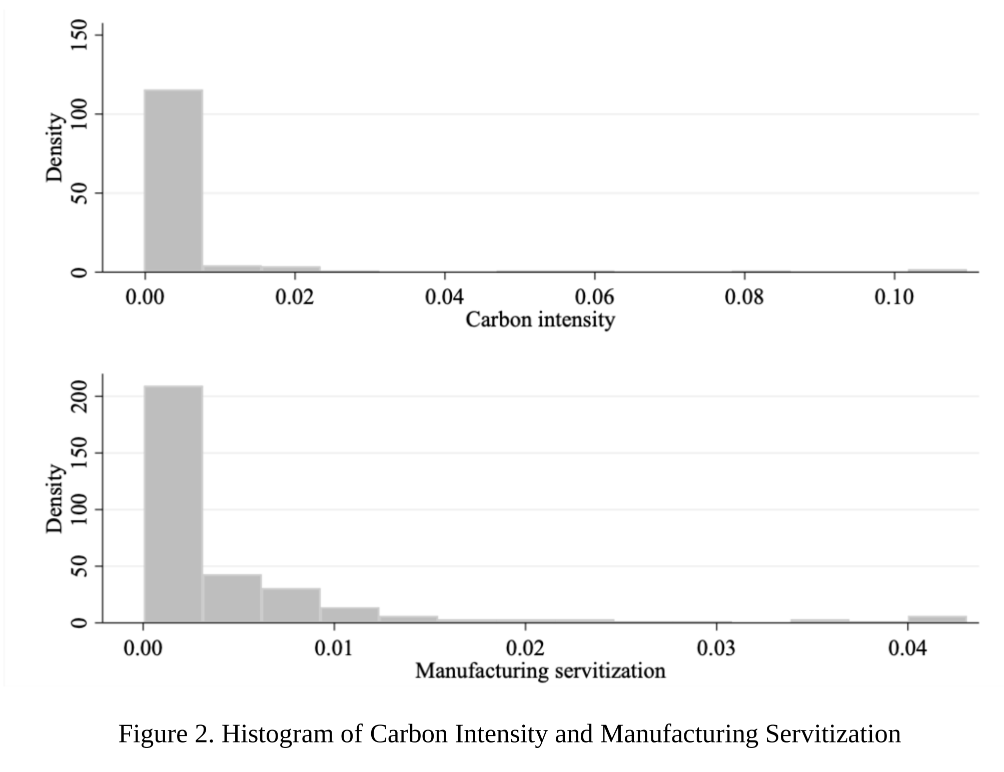

Figure 2. Histogram of Carbon Intensity and Manufacturing Servitization

4.1.4 Control variables ($Control$)

Based on the previous analysis, this study selects the following control variables: R&D intensity (*Rd*) is expressed as the ratio of R&D investment to total assets. In general, the carbon intensity index decreases with progress in R&D innovation and carbon governance technology. Return on assets (*Roa*) is expressed as the ratio of net profit to the average balance of total assets. The average balance of total assets is the average of total assets at the end of the period and total assets at the end of the same period last year. The improvement in the asset return rate can provide a material basis for carbon management and trading. Disclosure of information (*Defic*), i.e., whether to disclose the deficiencies of the company in the social responsibility report, takes the value 1 for disclosure and 0 for non-disclosure. Promoting enterprises to be more proactive in disclosing environment, society, and governance (ESG) information is conducive to developing more standardized carbon strategies and reducing the risks and costs of carbon management. Capital intensity (*Capital*) is expressed as the ratio of paid-in capital (per million) to the number of employees. In the process of moving towards low energy consumption and low emissions, enterprises need to improve energy and energy-saving technologies, and capital will inject vitality into industrial restructuring and scientific and technological innovation. The ratio of intangible assets (*Intang*) is expressed as the ratio of net intangible assets to total assets. The ratio of intangible assets reflects the internal asset structure of an enterprise, while carbon emission rights are also a part of intangible assets.

4.2 Data description

The original data used in this study has been obtained from listed company data, environmental performance data, and thematic data, collected by the CSMAR. According to the industry classification results of listed companies issued by the China Securities Regulatory Commission, this study selects the data of China's listed manufacturing companies from 2007 to 2020 as the research scope and processes the samples as follows: (i) The samples of companies listed after 2018 were eliminated to ensure the stable operation of sample enterprises for more than three years. (ii) Enterprises with missing data or bankruptcy were eliminated to ensure the continuity and availability of data during the research period. (iii) Continuous variables were winsorized at 1% to reduce the interference of outliers. The samples are unbalanced panel data, covering 26 out of 32 provinces and autonomous regions in China and 24 out of 31 manufacturing subsectors, with a time span of 2007 to 2020. The descriptive statistics of the main variables are shown in Table 1. In addition, a variance inflation factor (VIF) test was performed. The variables are considered to display multicollinearity if the maximum VIF > 10. The maximum VIF value of the sample in this paper is 1.11, which excludes the effect of multicollinearity on the model regression.

Table 1. Descriptive Statistics of Variables

Variable	Meaning	Obs	Mean	Std.dev.	Min	Max
Cei	Carbon intensity	213	0.004	0.015	0.000	0.110
Service	Servitization of manufacturing	213	0.005	0.008	0.000	0.043
Rd	Research and development intensity	207	0.029	0.021	0.001	0.090
Roa	Return on assets	213	0.057	0.062	-0.149	0.236
Defic	Disclosure of information	213	0.066	0.248	0.000	1.000
Capital	Intensity of capital	213	0.221	0.297	0.012	2.014
Intang	Ratio of intangible assets	213	0.042	0.031	0.000	0.203

5. EMPIRICAL ANALYSIS

5.1 Benchmark regression results

The *p*-value of Hausman's test is 0.000, which suggests that the fixed utility model should be used instead of the random utility model. Table 2 shows the benchmark regression results for the fixed effects of the controlling companies and the years from 2007 to 2020. The results show that $Service$ and Cei are always negatively correlated, regardless of whether the controlled variables are added, and were significant at least at the 10% level. The empirical results support Mont's (2002) view on the environmental effects of servitization transformation; that is, manufacturing servitization has a positive effect on reducing carbon intensity. In the face of severe climate problems, the manufacturing industry, as one of the main sources of global greenhouse gas emissions, urgently requires green transformation and low-carbon development. Manufacturing servitization is an important way to achieve growth in the global value chain and industrial transformation and has a potential spillover effect on carbon emission reduction. This section verifies the positive correlation between manufacturing servitization and carbon emission reduction, thus providing theoretical and countermeasure references for optimizing the industrial structure and improving manufacturing carbon productivity.

In terms of the control variables, increased R&D investment is negatively correlated with carbon intensity. Enterprises increase investment in R&D, which will enable new technologies to be applied to production links, improve production efficiency, reduce production costs, and promote energy conservation and emission reduction. ROA is negatively and significantly related to carbon intensity. Therefore, while increasing the carbon supervision of enterprises, it is necessary to focus on guiding them to develop new profit spaces. Information disclosure is inversely related to carbon intensity. Carbon emissions are an important manifestation of corporate social responsibility (CSR). Promoting companies to publish high-quality ESG reports can help achieve their carbon targets. Capital intensity is negatively related to carbon intensity. The increase in per capita capital helps improve both the skill level of the personnel and equipment technology, thus improving carbon efficiency. Additionally, a complete and dynamic carbon capital market should be gradually established to facilitate the low-carbon pace of high-carbon industries. The relationship between the intangible asset ratio and carbon intensity is not significant. This could be because, for the manufacturing industry, intangible and tangible assets need to coexist to affect carbon emission reduction; indiscriminate increases in the proportion of intangible assets may cause inefficient resource waste.

Table 2. Results of Benchmark Regression

	(1)	(2)	(3)
Service	-0.046** (0.027)	-0.079* (0.047)	-0.076* (0.046)
Rd		-0.110** (0.051)	-0.126** (0.061)
Roa		-0.036* (0.021)	-0.042* (0.024)
Defic			-0.003** (0.001)
Capital			-0.005* (0.003)
Intang			-0.048 (0.043)
Fixed effects	Yes	Yes	Yes
R^2	0.002	0.047	0.063
Observations	213	207	207

Note: *, **, and *** represent significance at the 10 %, 5 %, and 1% levels, respectively. Robust standard errors are shown in parentheses.

5.2 Robustness test

5.2.1 Endogeneity test

Low-carbon-intensity manufacturing companies have higher technology levels and lower production costs and, therefore, possess more resources for servitization transformation. In addition, carbon intensity is affected by several factors. Although the fixed effects alleviated the estimation bias to some extent, they could not completely cover the possible influencing factors. To avoid the endogeneity problems caused by the reverse influence and omitted variables, the $Service$ with a lag of one period was used as the instrumental variable (Zhu *et al.*, 2019; Xu *et al.*, 2017) to estimate the influence coefficient on Cei through Two-Stages Least Square (2SLS) and System Gaussian Mixed Model (GMM), as shown in columns 1 and 2 of Table 3.

5.2.2 Transform independent variable measurement method

First, manufacturing servitization, without winsorization, is used for regression to judge whether the results are affected by sample processing, as shown in column 3 of Table 3. Second, the proportion of non-primary business profits replaces the proportion of non-operating revenue as the measurement method of manufacturing output servitization for regression, and the results are shown in column 4.

5.2.3 Replacement regression method

The results obtained on replacing the fixed effects with random effects FGLS are as shown in column 5 of Table 3.

Table 3. Regression Results of Robustness Testing

	(1) FD-2SLS	(2) GMM	(3) Non-winsored	(4) Proportion of non-primary business	(5) FGLS
Service	-0.138*	-0.052*** (0.005)	-0.066* (0.039)	-0.001** (0.001)	-0.077* (0.048)
Control variables	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes
R^2			0.064	0.334	0.063
Observations	82	80	207	207	207

Note: ** and *** represent significance at the 5% and 1% levels, respectively. Robust standard errors are shown in parentheses. The test results for the validity of the instrumental variables and the regression results of the control variables are omitted and are available upon request.

Columns 1 and 2 in Table 3 show that after the endogeneity test, the regression coefficient sign does not change, and the results are still significant. In addition, neither the result of the weak identification test nor that of the under-identification test can deny the validity of the instrumental variable. In this result, bidirectional causality is excluded to a certain extent, and manufacturing servitization can be considered to have a negative effect on carbon intensity. Thus, **Hypothesis 1** is verified. Columns 3-5 show that the direction and significance of the variables do not change whether the explanatory variable measurement method is changed or the regression method is replaced. Therefore, the results in Table 3 show that the core conclusions of this study regarding the inhibitory effect of manufacturing servitization on carbon intensity are robust and reliable.

5.3 Heterogeneity analysis

5.3.1 Enterprise heterogeneity

Due to variances in the nature of enterprises, the impacts of manufacturing servitization on carbon emissions are also different across various industries. Manufacturing enterprises are divided into state-owned enterprises (SOEs), private enterprises, and others to analyze the heterogeneity of the nature of enterprises. The regression results on the heterogeneity of firm nature are shown in columns 1-3 of Table 4. As per China's Statistical Classification of Large, Medium, and Micro Enterprises, the listed enterprises in the sample are all large in an absolute sense. In order to study the different effects of servitization on carbon emission reduction of manufacturing enterprises of different relative sizes, this section divides enterprises into relatively large, medium, and small enterprises according to the number of employees. The results are shown in columns 4-6.

Table 4. Enterprise Heterogeneity Analysis Results

	(1) SOEs	(2) Private Enterprise	(3) Others	(4) Relatively large	(5) Relatively medium	(6) Relatively small
Service	-0.079* (0.045)	-0.125* (0.069)	-0.011*** (0.002)	0.008 (0.056)	-0.027* (0.016)	-0.102* (0.061)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.117	0.261	0.779	0.166	0.243	0.169
Observations	91	83	16	66	69	72

Note: *, **, and *** represent significance at the 10 %, 5 %, and 1% levels, respectively. Robust standard errors are shown in parentheses. The estimated results for the control variables are omitted and are available upon request.

From Table 4, columns 1-3, the servitization of private manufacturing enterprises restrains carbon emissions the most. This may be due to the fact that SOEs are usually large, thereby transitioning relatively slowly. Private manufacturing enterprises have greater potential for servitization and lower thresholds, are mostly in competitive industries, and their transformation is more flexible, thereby exerting a more obvious impact on carbon emission reduction. In addition, regarding carbon regulations, SOEs will adopt a more conservative attitude with the endorsement of the government, while private enterprises will either be willing or will have to adopt radical changes. Therefore, we should deepen the reform of SOEs, strengthening the restraint effect of various laws and systems on them and enhancing their consciousness towards market competition and innovation.

As can be seen in columns 4-6 of Table 4, the servitization of relatively small manufacturing enterprises has the greatest effect on carbon emission reduction. Due to their scale and, therefore, higher adjustment costs and cycles in the process of servitization transformation, the effect on carbon emission reduction is not so obvious among medium and large enterprises. Relatively small enterprises are more flexible in this respect and can complete the servitization transformation trial process with lower adjustment costs. Therefore, it is necessary to focus on improving the service level of the manufacturing industry so that limited resources can play a greater role in carbon emission reduction. The pilot service transformation of the manufacturing industry should be prioritized, with the formation of a batch of replicable and popularized low-carbon technologies and development models for comprehensive energy conservation and emission reduction.

5.3.2 Regional and industry heterogeneity

Different types of regions may have varied carbon emission reduction effects owing to different development stages, marketization levels, and openness. Generally, the level of economic and technological development in China declines from the eastern coastal areas towards the central and western inland areas. Per capita GDP in China's coastal areas, for example, was about 1.5 times that of inland areas, according to 2021 data. Regional heterogeneity is analyzed according to the classification of China's coastal and inland economic belts, as shown in columns 1 and 2 of Table 5. In addition, industries with different factor intensities have different servitization capabilities and may have different impacts. By subdividing industries according to factor intensity, this study explores the relationship between output servitization and carbon intensity in different industries. The results are shown in columns 3-5.

Table 5. Heterogeneity Analysis Results of Region and Industry

	(1) Coastal area	(2) Inland areas	(3) Technology intensive	(4) Labor intensive	(5) Capital intensive	(6) Capital High	(7) Capital Low
Service	-0.078* (0.042)	-0.025*** (0.007)	-0.009* (0.005)	-0.597*** (0.127)	-1.217* (0.644)	-0.183* (0.099)	-0.008** (0.003)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.087	0.308	0.195	0.408	0.040	0.153	0.316
Observations	151	56	143	26	33	103	104

Note: *, **, and *** represent significance at the 10 %, 5 %, and 1% levels, respectively. Robust standard errors are shown in parentheses. The estimated results for the control variables are omitted and are available upon request.

As can be seen from columns 1 and 2 of Table 5, the effect of servitization on carbon emission reduction in the developed (eastern coast) regions is greater than that in the less developed (central and western inland) areas in China. The developed economy with a relatively higher degree of marketization and interaction with the outside world in eastern China helps to promote the transformation of the manufacturing sector and allows the positive externality of servitization transformation to reduce carbon intensity. At the same time, due to the weak economic foundation and slow process of system transition in central and western China, the process and efficiency of servitization are significantly different. Therefore, carbon intensity depends not only on production technology but also on resource allocation based on the economic system and development level, which also affects the carbon emission reduction effect of manufacturing servitization.

Columns 3-5 of columns show that manufacturing servitization in capital-intensive industries has the greatest impact on carbon intensity. This may be due to the fact that capital-intensive industries have relatively high requirements of financing services. At the same time, to improve the core competitiveness of products, it is necessary to integrate products with services having capital attributes and optimize the entire value chain to reduce carbon emissions, by improving the added value of products and productivity. Compared with capital-intensive industries, labor-intensive industries are primarily low-value-added industries, and their production and operation activities mainly rely on physical objects. The services invested in labor-intensive manufacturing are mainly low-end, resulting in the limited effect of servitization on carbon emission reduction. Enterprises in technology-intensive industries still focus on technology R&D and innovation, and excessive focus on improving servitization levels may weaken their own R&D and business activities, which is not conducive to the reduction of carbon intensity. Moreover, China's technology-intensive industries face a lack of high-end services and limited technology imports. As a result, increasing enterprise servitization in this industry may not improve carbon productivity.

To sum up, **Hypothesis 4** is verified. In order to further verify the role of capital, the group test is conducted according to the 50% quantile of capital intensity in the control variable, and the results are shown in columns 6 and 7 of Table 5. In the high capital intensity group, the impact of manufacturing servitization on carbon intensity is much greater than that of the low capital intensity group. This shows that the green development of the manufacturing industry needs the support of the capital market. Therefore, to improve the low-carbon development capacity of the manufacturing industry, it is necessary to increase capital investment in enterprises. Developed regions relatively possess and have the ability to attract abundant capital, which explains the reason for the strong carbon emission reduction effect of manufacturing servitization in eastern China.

5.4 Mediating effect analysis

According to the previous analysis, this section tests the mediating effect of the two variables. Firstly, green total factor productivity ($\boldsymbol{Gtfp}$) is used to express the effect of technology innovation. $\boldsymbol{Gtfp}$ is measured using the Data Envelopment Analysis method, with employees and capital as input variables and carbon emissions and revenue as output variables. The regression results are shown in columns 1 and 2 of Table 6. Secondly, the growth rate of operating income ($\boldsymbol{Growth}$) represents the value-added effect. $\boldsymbol{Growth}$ is expressed as the value of the difference between the amount of operating income in the current period and that in the previous period, divided by the amount of operating income in the previous period. The regression results are shown in columns 3 and 4.

Table 6 Analysis of Mediation Effect

	(1) *Gtfp*	(2) *Cei*	(3) *Growth*	(4) *Cei*
Service	1.579* (0.863)	0.031 (0.088)	0.160* (0.090)	-0.114* (0.068)
Gtfp		-0.005* (0.003)		
Growth				-0.005* (0.003)
Control variables	Yes	Yes	Yes	Yes
Fixed effects	Yes	Yes	Yes	Yes
R^2	0.056	0.108	0.021	0.028
Observations	108	108	206	206

Note: *, **, and *** represent significance at the 10 %, 5 %, and 1% levels, respectively. Robust standard errors are shown in parentheses. The estimated results for the control variables are omitted and are available upon request.

The $Service$ coefficient in Column 1 of Table 6 is significantly positive, indicating that servitization transformation has a promoting effect on technological innovation. The coefficient of $Gtfp$ in Column 2 is significantly negative, so it can be presumed that technological innovation is the intermediary channel for manufacturing servitization to affect carbon intensity. The output servitization of manufacturing enterprises has stimulated the vitality and space of green technology progress and promoted the carbon efficiency of products and processes. **Hypothesis 2** is validated. In column 3, the coefficient of $Service$ is positive, indicating that service is conducive to the expansion of enterprise revenue scale. In column 4, the coefficient of $Growth$ is negative, indicating that the expansion of the revenue scale of China's listed manufacturing industry has not led to energy waste. Although scale expansion will increase total carbon emissions, it can dilute carbon intensity through scale effects. **Hypothesis 3** is validated.

6. CONCLUSION

This study empirically tests the impact of manufacturing output servitization on carbon intensity, analyzing the heterogeneity based on the types of manufacturing enterprises, regional economic development levels, and industry factor density. The main conclusions are as follows: (1) Servitization of manufacturing is conducive to reducing carbon intensity. (2) The heterogeneity test shows that the servitization of business entities within different types of enterprises, industries, and regions will produce different levels of carbon emission reduction. Compared with SOEs, the carbon emission reduction due to servitization in private enterprises is more evident. Relatively small-scale listed manufacturing companies have the largest carbon emission reduction effect on output servitization. Compared with developed regions, the servitization of manufacturing in developing regions plays a smaller role in promoting carbon emission reduction. The servitization transformation of capital-intensive manufacturing industries has a greater inhibitory effect on carbon intensity than the labor- and technology-intensive manufacturing industries. (3) GTFP and the growth rate of operating income are the mediating variables in the effect of manufacturing output servitization on carbon emissions. Manufacturing servitization transformation reduces carbon intensity through technological innovation and value-added effects. Many countries undergoing industrial transformation are mindful of eco-efficiency. This study draws on China's empirical data to have certain implications for countries in the process of industrialization or reindustrialization and is committed to reducing environmental pollution. In addition, unlike previous discussions on the servitization of manufacturing inputs, this study provides evidence that the servitization of manufacturing output reduces carbon intensity.

6.1 Management insights

While the study focuses on economic analysis, it also provides possible managerial insights. In the past, many studies have emphasized that environmental costs, as an exogenous variable, force manufacturing enterprises to improve competitiveness and environmental performance. However, this paper emphasizes that output servitization, as an independent choice of manufacturing enterprises, objectively promotes eco-efficiency. Given enhanced carbon regulation, this increase in eco-efficiency can also help improve business performance by reducing the carbon costs associated with production (Chang *et al.*, 2021). This is especially noteworthy for manufacturing enterprises with high energy consumption, high pollution, and insufficient service sectors. Another management insight that can be obtained from the heterogeneous relationship between manufacturing output servitization and carbon intensity is that manufacturing enterprises need to consider the location, scale size, and types of new business. Regional, firm and industry heterogeneity causes a long-term increase in carbon cost due to the strengthening of carbon regulation, to vary (Zong and Gu, 2021). As observed, this carbon risk is relatively weak for developed regions, capital-intensive industries, or relatively small-scale enterprises, which is more conducive to the growth of enterprise performance. However, manufacturing enterprises at the level of low carbon emission reduction effect should not give up their efforts in this regard. As service elements have positive significance for consolidating consumer recognition, improving market acceptance, and extending the life cycle of enterprises. Manufacturing enterprises should actively adjust organizational structure, talent policy, management strategy, etc., in order to better cope with the trend of servitization.

Our study also suggests the role of technological innovation and value-added as transmission channels. The rise of new Internet technologies has forced enterprises to build new business models and migrate from the traditional product-centric to the (digital-based) service-oriented approach (Paiola and Gebauer, 2020). Manufacturing enterprises should take the initiative to establish strong connections with service elements and actively transform to digital and green services to cope with the challenges of carbon regulation. In addition, this paper believes that the disclosure of CSR reports is also an important means of self-supervision. Compliance with certain rules and standards plays a positive role in preventing waste and improving performance. Therefore, requiring companies to voluntarily disclose CSR reports is a catalyst for achieving sustainable development.

6.2 Policy Implications

Extensive growth cannot support high-quality development. Many manufacturing enterprises reduce pollution emissions and improve eco-efficiency by controlling natural resource input and direct industrial waste discharge. While this is beneficial to energy conservation and emission reduction, it may dampen economic output. The servitization model has obviously organizational advantages in ecological benefits potential, which is conducive to encouraging manufacturers to change the traditional value creation and resource utilization mode.

Convergence between manufacturing and services is achieved in a synergistic way in different locations, domestically and even globally, with the support of technology. Some firms may experience higher production costs and lower performance levels at the initial stage of servitization. They fall into the "service trap" by adding unnecessary and excessive services regardless of the actual effect, which breeds waste and increases carbon emissions. At this time, from the perspective of enterprises, it is necessary to start from their own and environmental characteristics to prevent blind increase in service input and output, strengthen the dynamic monitoring of internal energy operation, and promote the monitoring and fine management of energy consumption in the production process. From the perspective of policy makers, it is necessary to improve measures to ensure that enterprises improve quality and efficiency, pay more attention to the use of laws and regulations, optimize the management of energy consumption standards, and gradually eliminate backward enterprises and inefficient production capacity with excessive energy consumption and low efficiency. In addition, in recent years, some developed countries have fallen into industrial hollowing out and put forward the slogan of reindustrialization or revitalization of the manufacturing industry. Manufacturing servitization is not to abandon the manufacturing industry but a rational choice for manufacturing enterprises to enhance their competitiveness according to the actual situation of enterprises and the development environment of the industry. The servitization transformation should be based on the real economy, and its essential purpose is to improve the modernization level of the manufacturing industry. Backward countries should pay attention to this phenomenon, respect the law of social and economic development, and focus on improving industrial productivity in the process of pursuing green development rather than premature deindustrialization.

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