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Do the servitization of manufacturing inputs and outputs have the same impact on carbon emission efficiency? Evidence from the “Belt and Road” Initiative

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Article

Keywords: Carbon emission efficiency, manufacturing input servitization, manufacturing output servitization, Belt and Road Initiative (BRI)

Posted Date: August 20th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10005515/v1

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Additional Declarations: No competing interests reported.

Abstract

The impact of the manufacturing servitization transformation on carbon emission efficiency remains controversial. Based on data from the EORA input-output table, the study employs a super-efficiency SBM-GML model to measure carbon emission efficiency and examines the effects of input and output servitization on manufacturing carbon emission efficiency, respectively. The findings reveal that manufacturing servitization significantly suppresses carbon emission efficiency, with both input and output servitization exhibiting a U-shaped nonlinear relationship, indicating a "green cost" during the early stage of transformation. Cost effects and value-added effects are identified as the core transmission mechanisms. A higher proportion of knowledge and technology intensive service inputs and a greater share of high value-added manufacturing significantly mitigate the negative impact of servitization. This paper elucidates the transmission mechanisms and stage-dependent characteristics through which manufacturing servitization affects carbon emission efficiency, providing empirical evidence for Belt and Road partner countries to promote the transformation of manufacturing servitization and achieve the United Nations Sustainable Production Goals.

1. Introduction

As the primary source and core carrier of carbon emissions, the green and low-carbon transformation of global manufacturing directly affects the realization of the United Nations Sustainable Development Goals and the process of high-quality economic development. The International Energy Agency (IEA) confirmed in its *Global Energy Review 2026* released in April 2026 that global energy-related carbon dioxide emissions totaled approximately 3.84 billion tons in 2025, and the absolute reduction in carbon emissions remains far from the UN climate targets. The organization of global industrial production is undergoing a notable shift: the value chain focus of manufacturing is increasingly extending from physical production to the integration of “products and services”-i.e., manufacturing servitization. However, against the backdrop where carbon emission efficiency directly determines overall emission levels[1–2],whether this new servitization-driven manufacturing model necessarily translates into higher carbon emission efficiency remains empirically unclear.

On the one hand, manufacturing servitization may directly enhance carbon emission efficiency through multiple micro-mechanisms. First, the “softening” effect of factor structure implies that firms increase their input of knowledge- and technology-intensive services such as R&D, design, and industrial software development, while relatively reducing over-reliance on high-energy, high-emission physical capital and primary factors, thereby improving total factor productivity (TFP) and energy use efficiency. Second, through technology spillovers and management empowerment-by purchasing or embedding digital services such as industrial internet and intelligent operations and maintenance-manufacturing firms can monitor energy consumption and emissions more accurately and overcome efficiency losses caused by information asymmetry. Third, the transformation of business models, i.e., shifting from simply selling products to providing lifecycle solutions, incentivizes manufacturers to introduce eco-design concepts at the design stage and extend product service life, thereby reducing embodied carbon emissions per unit of output at the source.

On the other hand, this structural transformation also entails unintended environmental costs. The expansion of service activities lengthens and complicates supply chains, potentially increasing indirect energy consumption from transportation, warehousing, and business travel. Meanwhile, cost reductions driven by productivity improvements may trigger the “rebound effect” of the Environmental Kuznets Curve (EKC)[3], i.e., stimulating aggregate demand expansion and thus offsetting the technological green dividend. Furthermore, digital services trade rules dominated by developed economies may reinforce the existing international division of labor, causing Belt and Road partner countries to fall into high-carbon service lock-in as they undertake service outsourcing, further undermining the potential emission reduction benefits of servitization transformation.

A consensus has yet to be reached regarding the relationship between manufacturing servitization and carbon emission efficiency and its underlying mechanisms. Some studies argue that embedding service factors optimizes production resource allocation, reduces inefficient energy consumption and production redundancy, and thus contributes to emission reduction and efficiency improvement in manufacturing. Other studies point out that the early stage of manufacturing servitization transformation suffers from cost-adjustment lags and resource misallocation, and excessive embedding of service factors may increase energy consumption pressure. The complex relationship and dynamic mechanisms between the two remain to be rigorously tested empirically. More critically, the connotation of servitization transformation extends beyond cost-driven factor substitution on the input side to include demand-driven value creation models on the output side. However, existing research rarely considers the heterogeneous effects of input and output servitization simultaneously, making it difficult to precisely identify the green effect

pathways of servitization transformation. Currently, Belt and Road partner countries encompass economies at different income levels and stages of industrialization and generally face external shocks from the reshaping of digital services trade rules, making them an ideal sample for examining the environmental effects of manufacturing servitization.

Based on this, this paper constructs an input-output dual-dimensional servitization impact pathway within the framework of carbon emission efficiency, delves into the internal mechanisms through which manufacturing servitization affects carbon emission efficiency, and reveals possible green transmission blockages. This study aims to clarify three core research questions: First, to examine the direction, intensity, and dynamic characteristics of the impact of manufacturing input and output servitization on carbon emission efficiency in Belt and Road partner countries. Second, to design and test the transmission roles of cost, value-added, and technology dimensions within the overall research framework. Third, to explore the moderating effects of factor endowment structure, industry characteristics, and cross-country income-level heterogeneity on the above relationships. This research thereby fills a gap in the existing servitization literature concerning multivariate chain-like mechanism analysis, enriches the research system on green transformation of manufacturing and low-carbon economic development, and provides rigorous theoretical support and precise empirical reference for countries and regions to promote servitization upgrading and coordinate high-quality industrial development with sustainable production goals.

2. Literature Review

Current research on carbon emission efficiency has focused primarily on the optimization of measurement methods and the identification of influencing factors. Scholars' measurement of carbon emission efficiency has evolved from single-factor approaches (Kaya et al., 1993) to total-factor frameworks. The environmental consequences of manufacturing servitization, however, have diverged into three strands of debate: promoting effects[4], inhibiting effects[5], and nonlinear effects[6].

Measurement and influencing factors of carbon emission efficiency. Under the total-factor framework, carbon emission efficiency is measured using either parametric stochastic frontier analysis (SFA) or non-parametric data envelopment analysis (DEA), with the latter being more widely applied due to its ability to automatically assign weights to indicators and estimate sources of inefficiency. However, traditional DEA suffers from slack variable and radial selection problems[7]. Scholars have subsequently adopted non-radial models such as super-efficiency SBM to improve upon it[8] and have linked them with the GML index to enable dynamic intertemporal analysis[9]. Measurement methods for manufacturing carbon emission efficiency have largely focused on the SBM directional distance function [10], and some scholars have used super-efficiency SBM to measure carbon efficiency in China's manufacturing sector[11]; however, cross-country comparative studies remain relatively scarce, and accurate assessments for Belt and Road partner countries are still lacking. Regarding influencing factors, empirical modeling has been conducted along two dimensions: internal and external. Internal factors include technology effects, structural effects, and scale effects, with technology effects being particularly significant[12–13]. External factors mainly include environmental regulation[14], foreign direct investment[15], and government economic institutional participation[16]. As the transformation of development patterns has become the main pathway to carbon emission reduction, service factors have been recognized as having ecological efficiency implications. Given that manufacturing is a high-quality development sector, manufacturing servitization has consequently been placed on the research agenda[17]. Early studies largely discussed the economic effects of servitization, while environmental effect studies have mostly started from the perspective of input servitization. Due to differences in trade patterns and regions, no consensus has been reached on the environmental effects of input servitization.

Environmental effects of manufacturing servitization. Existing research on the economic effects of servitization has largely focused on firm performance[18] and economic consequences such as global value chain participation[19]. Research on environmental effects is still in its early stages and exhibits considerable divergence. The first strand-promoting effects-finds that, from the perspective of input servitization, the integration of productive or consumer services with manufacturing can enhance regional carbon emission efficiency[20–21]. The low-pollution, high-value-added characteristics of the service sector can facilitate the optimization of energy allocation and process technology innovation in traditional manufacturing[3]. A few scholars have considered output servitization and also found environmental promoting effects[22]. The second strand-inhibiting effects-argues that the agglomeration of high-end services and traditional manufacturing exacerbates environmental pollution[23–24]. The main reason input servitization inhibits efficiency growth is the low-end and low-quality nature of service inputs, reflecting Baumol's cost disease in the

service sector. The third strand-nonlinear effects-has empirically confirmed that servitization exhibits a U-shaped [25] or an inverted U-shaped[26] effect on manufacturing total factor productivity from an economic perspective. Building on this, some scholars have further identified a nonlinear relationship between manufacturing input servitization and eco-efficiency[6]. The above divergence suggests that the environmental effects of manufacturing servitization depend on the quality of service factors and the specific choices of servitization transformation pathways, and that nonlinear effects may be prevalent.

The above studies have deepened our understanding of the relationship between manufacturing servitization and carbon emission efficiency, yet several gaps remain. First, existing literature on carbon emission efficiency measurement has concentrated on provincial, municipal, and industry levels[11], while cross-country comparative studies at the national level are relatively weak, and accurate assessments of manufacturing carbon emission efficiency in Belt and Road partner countries are still lacking. Second, in terms of influencing factors, extant research has largely proceeded from traditional dimensions such as technology, structure, scale, and environmental regulation[14]; analyses that incorporate manufacturing servitization-as an industrial upgrading strategy-into the framework of carbon emission efficiency remain insufficient. Third, regarding the environmental effects of manufacturing servitization, the literature presents three competing views (promoting, inhibiting, and nonlinear), but most studies remain confined to the input servitization perspective[18] and have not systematically integrated the heterogeneous transmission pathways of input versus output servitization. Further in-depth analysis of the mechanisms is urgently needed. Therefore, this paper distinguishes manufacturing servitization into two dimensions-input and output-and, based on data from Belt and Road partner countries, investigates their respective internal mechanisms and transmission pathways affecting carbon emission efficiency, while empirically testing for nonlinear effects.

3. Mechanism analysis and research hypotheses

This chapter constructs a mechanism design through which manufacturing servitization affects manufacturing carbon emission efficiency, as illustrated in Fig. 1.

3.1. Baseline impact hypothesis

Manufacturing input servitization is essentially a systematic substitution of high-carbon physical factors with clean service factors. According to the theory of industrial structure evolution, economic growth is accompanied by the transfer of factors from high-energy-consuming heavy and chemical industries to lightweight, high-value-added service industries. The increase in intermediate service inputs such as R&D, design, and digital management is essentially a process of replacing traditional energy-intensive physical capital with clean factors such as information and knowledge. This “factor softening” generates a dual emission reduction effect: first, it directly reduces the dependence on fossil fuels per unit of output, cutting carbon emissions at the source[4]; second, through the penetration of service factors such as clean energy technology access, it improves the overall energy use efficiency of manufacturing. At the same time, service providers, leveraging their scale and technological advantages, can offer carbon management solutions at a marginal cost lower than that of firms’ own operations[21], enabling firms to achieve emission reduction targets at a lower opportunity cost under given resource constraints. Notably, the impact of input servitization on carbon emission efficiency may be nonlinear: in the early stage, the factor substitution effect significantly promotes carbon efficiency; however, after service input exceeds a certain threshold, excessive procurement may raise transaction costs and organizational complexity, generating diminishing or even reverse inhibiting effects. Accordingly, we propose:

H1a. *Manufacturing input servitization can improve manufacturing carbon emission efficiency, but a nonlinear relationship may exist.*

Manufacturing output servitization marks a strategic shift in the center of value creation from tangible processing to intangible services. According to the global value chain and smile curve theories, the manufacturing stage occupies the low-value-added segment while also being a concentration area of energy consumption and carbon emissions[27]. Firms extending toward both ends-R&D, design, branding, and services-are essentially making a structural transition toward low-material-consumption, high-value-return activities, thereby generating greater economic output with less physical resource input and promoting the gradual decoupling of economic growth from carbon emissions. At the same time, market demand is shifting from a single product function to comprehensive service value that includes environmental protection and sustainability. By adopting green service models such as lifecycle management and shared leasing, firms deeply bind their economic returns to the long-term energy efficiency and

recyclability of products[28]. This market-driven long-term incentive mechanism forces firms to continuously reduce carbon emissions during the use, maintenance, and even disposal stages in the pursuit of maximizing service profits, creating an inherent demand-side impetus for improving carbon efficiency. Similarly, output servitization may have a nonlinear relationship with carbon emission efficiency: moderate service extension helps increase value added and reduce carbon intensity, but overly rapid expansion that dilutes core capabilities or raises management costs may weaken the improvement effect.

H1b. *Manufacturing output servitization can improve manufacturing carbon emission efficiency, but a nonlinear relationship may exist.*

3.2. Mediation effect hypotheses

(1) Inter-industry cost effect.

Manufacturing input servitization changes the intermediate costs required by manufacturing, affecting the substitution of traditional manufacturing energy by producer services, thereby altering manufacturing carbon emission efficiency. Specifically, it operates through sub-channels in both soft and hard costs, including saving fixed asset investment, reducing inventory, outsourcing services, and lowering transaction costs. The substitution effect between service factors and fossil fuels in the production structure[29] reduces energy-intensive fixed asset investment[3] and simultaneously lowers service procurement costs and marginal carbon emissions per unit of output[30]. The servitization-driven on-demand production model improves capacity utilization, reduces warehouse energy consumption and resource waste from unsold products[3], thereby improving inventory to avoid carbon pollution[31]. Outsourcing non-core services allows firms to focus on breakthroughs in green core technologies[31–32], while outsourcing pollution control activities leverages the pollution abatement technologies of specialized service providers to achieve cost savings and environmental performance improvements. The integration of manufacturing and services shortens the temporal and spatial distance of transactions, enabling the acquisition of tacit knowledge through in-depth service interactions, thereby reducing transaction costs[29] while maintaining green competitive advantages.

H2a. *The inter-industry cost effect is an important mechanism through which input servitization affects carbon emission efficiency.*

(2) Intra-industry value-added effect.

Manufacturing output servitization changes the value added within manufacturing, affecting the propensity for green transformation within the sector and thereby altering manufacturing carbon emission efficiency. Specifically, it operates through sub-channels in both supply and demand aspects, including influencing manufacturing value chain upgrading and adaptation to low-carbon trade. From the supply side, the substitution of low-technology factors by service factors strengthens the division of labor between the two industries, lays the technological foundation for value chain extension toward R&D and branding, and encourages the agglomeration of green technology factors in high-efficiency manufacturing sectors, generating a “structural dividend” in economic output. From the demand side, as environmental awareness grows globally, various carbon tariffs and environmental protection provisions have been incorporated into trade agreements, which in turn force manufacturing sectors in different countries to accelerate the restructuring of their export product mixes toward low-carbon products[33], enabling them to accurately capture customers’ green consumption demands[34] and enhance the dynamic adaptability of manufacturing to international low-carbon standards [35].

H2b. *The intra-industry value-added effect is an important mechanism through which output servitization improves carbon emission efficiency.*

(3) Comprehensive technology effect.

In addition to the above two indirect mechanisms, the manufacturing servitization process itself is accompanied by the introduction of advanced energy-saving technologies in the production sector. Moreover, the capital occupation resulting from green knowledge products in the service sector may lead some manufacturing sectors to reduce their own R&D investment in green patents, thereby affecting the manufacturing sector’s own green technology progress and green technology management efficiency. However, the adoption of carbon emission reduction technologies by the manufacturing sector also depends on multiple factors, including technological level, subsidy policies, and emission reduction performance. Therefore, the direction of the comprehensive technology

effect induced by servitization on a country's manufacturing carbon emission efficiency is difficult to determine a priori. The green technology progress and green technology efficiency embodied in input and output servitization await quantitative empirical testing.

4. Research design

4.1. Model specification

4.1.1. Benchmark regression model

To test Hypotheses 1a and 1b above, and drawing on existing servitization research models, we construct benchmark models (1) and (2) for the impact of manufacturing input servitization and manufacturing output servitization on manufacturing carbon emission efficiency, respectively.

$$CEE_{it} = a_o + a_1 Serin_{it} + a_2 \sum X_{it} + u_t + \sigma_i + \epsilon_{it}$$

1

$$CEE_{it} = b_o + b_1 Serout_{it} + b_2 \sum X_{it} + u_t + \sigma_i + \epsilon_{it}$$

2

Where CEE_{it} represents the level of manufacturing carbon emission efficiency; $Serin_{it}$ and $Serout_{it}$ denote manufacturing input servitization and manufacturing output servitization, respectively; a_o is the constant term; X_{it} is the set of control variables; u_t represents time fixed effects, σ_i represents country fixed effects, and ϵ_{it} is the error term. The subscripts i and t denote manufacturing in different countries and years, respectively, and the same notation applies throughout. To avoid potential heteroskedasticity issues that may arise from the two-way fixed effects model, heteroskedasticity-robust standard errors are employed.

Furthermore, to test for possible nonlinear relationships, the models with centered terms are specified as follows:

$$CEE_{it} = c_o + c_1 Serin_{it} + c_2 Serin_{it}^2 + c_3 \sum X_{it} + u_t + \sigma_i + \epsilon_{it}$$

1a

$$CEE_{it} = d_o + d_1 Serout_{it} + d_2 Serout_{it}^2 + d_3 \sum X_{it} + u_t + \sigma_i + \epsilon_{it}$$

2a

4.1.2. Mediation effect model

To test the mechanism parts of Hypotheses 2a and 2b, this section employs interaction terms for mechanism analysis and specifies the following econometric models, conducting tests at two levels:

$$M_{it} = \rho_o + \rho_1 Serin_{it} + \rho_2 \sum X_{it} + u_t + \sigma_i + \epsilon_{it}$$

3

$$CEE_{it} = \varphi_o + \varphi_1 Serin_{it} + \varphi_2 M_{it} + \varphi_3 M_{it} \times Serin_{it} + \delta_4 \sum X_{it} + u_t + \sigma_i + \epsilon_{it}$$

4

In Eq. (3), taking manufacturing input servitization as an example (with manufacturing output servitization following a similar pattern), M_{it} denotes the corresponding mechanism variable. In the first-level test, attention is focused on ρ_1, ; if it passes the significance test, the validity of the influence mechanism of manufacturing input servitization is confirmed. Eq. (4) represents the second-level test, with focus on φ_3 if it passes the significance test, it indicates the presence of a mechanism effect of *M* (the interaction term in the second-level test is centered). In addition, this model can satisfy the need to calculate the proportion of indirect effects in the mechanism analysis presented later.

To test the channel parts of the analysis in Hypotheses 2a and 2b, and following existing research practices, a two-step channel mechanism test is adopted, with the model specified as follows:

$$m_{it} = a_o + a_1 Serout_{it} + a_2 \sum X_{it} + u_t + \sigma_i + \epsilon_{it}$$

5

In Eq. (5), taking manufacturing output servitization as an example (with manufacturing input servitization following the same approach), m_{it} denotes the corresponding channel mechanism variable. If a_1 passes the significance test, it indicates the validity of the channel through which output servitization operates.

4.2. Variable and data description

4.2.1. Explained variable

Manufacturing carbon emission efficiency (CEE). This study uses the Super-SBM model to measure manufacturing carbon emission efficiency in Belt and Road partner countries, and combines it with the global benchmark GML index to dynamically examine carbon efficiency across countries, thereby accurately capturing the green development level of manufacturing in these partner countries.

(1) Indicator system

This paper selects annual data from 54 Belt and Road partner countries to measure manufacturing carbon emission efficiency. Due to data availability, the sample period is from 2013 to 2021, with dynamic results reported for 2014–2021. The variable selection and processing are described in Table 1 below.

Table 1
Indicator System for Manufacturing Carbon Emission Efficiency

Indicator category	**Indicator name**	**Specific indicator**	**Unit**
Input	Labor input	Total industrial labor force × wage share in manufacturing	thousand persons (10^3)
Input	Capital input	Manufacturing fixed capital consumption	million USD (current prices)
Input	Energy input	Energy consumption per unit GDP × manufacturing output	TJ(10^{12}J)
Output	Desirable output	Manufacturing value added	million USD (current prices)
Output	Undesirable output	Manufacturing CO2 emissions	Gg (thousand tons)

(2) Industry classification and country identification

For industry classification, following the EORA26 industry codes and existing practices, the manufacturing and service sectors in this paper are aggregated as shown in Table 2 below. For country identification, the three-letter country codes specified by the ISO 3166-1 standard are adopted.

Table 2
Industry Definition

Category	EORA26 code	Industry name in English
Manufacturing	C4	Food & Beverages
	C5	Textiles and Wearing Apparel
	C6	Wood and Paper
	C7	Petroleum, Chemical and Non-Metallic Mineral Products
	C8	Metal Products
	C9	Electrical and Machinery
	C10	Transport Equipment
	C11	Other Manufacturing
	C12	Recycling
Service	C16	Maintenance and Repair
	C17	Wholesale Trade
	C18	Retail Trade
	C19	Hotels and Restaurants
	C20	Transport
	C21	Post and Telecommunications
	C22	Financial Intermediation and Business Activities
	C23	Public Administration
	C24	Education, Health and Other Services

(3) Data sources
In Table 1, total industrial labor force is sourced from the World Bank's World Development Indicators (WDI) database, and the wage share in manufacturing comes from the manufacturing employment compensation data provided by the EORA input-output database. Manufacturing fixed capital consumption is obtained from the manufacturing fixed capital consumption account in the EORA database; this indicator is valued in current US dollars and reflects the flow level of capital services in the manufacturing production process. Energy consumption per unit of GDP is based on the International Energy Agency (IEA) and converted using manufacturing output from the EORA database, expressed in terajoules (TJ). Manufacturing value added data are from the EORA input-output tables, valued in current US dollars, which accurately reflect the newly created value of manufacturing production activities. Manufacturing CO2 emissions are also taken from the EORA input-output database, expressed in gigagrams (Gg). Slight missing data are filled using linear interpolation.

Furthermore, the research subject of this paper is a country's manufacturing sector as a whole. To ensure measurement validity, carbon efficiency is first measured for each manufacturing sub-sector C4-C12, and then the share of each sub-sector's total input in the overall manufacturing input is used as a weight to comprehensively calculate manufacturing carbon emission efficiency at the national level.

4.2.2. Core explanatory variables

Manufacturing input servitization ($Serin$). Based on the EORA input-output tables, this study measures manufacturing servitization in Belt and Road partner countries using the total consumption coefficient method. Compared with the direct consumption coefficient, this method incorporates the indirect consumption of service sectors by manufacturing, thereby more comprehensively revealing the intrinsic linkages between sectors. This measurement approach has been widely adopted in the manufacturing servitization literature.

Manufacturing output servitization ($Serout$). This is measured using the total allocation coefficient method, calculated as the share of manufacturing output allocated to service sectors. Specifically, input and output servitization are first measured for each manufacturing sub-sector C4-C12, and then the share of each sub-sector's total output in overall manufacturing output is used as a weight to comprehensively measure the overall manufacturing input and output servitization levels for each country.

4.2.3. Mediating variables

(1) Cost effect (Cost). Current methods for capturing the intermediate cost effect of manufacturing firms are relatively well developed, mainly using the intermediate input price method and the import share method. At the manufacturing industry level, it is common to use intermediate cost data directly from input-output tables. Referring to existing studies on cost effects in manufacturing and considering dimensional influences, this paper measures the cost effect as the ratio of log-transformed manufacturing intermediate costs to manufacturing value added. Data are sourced from the EORA input-output tables.

(2) Value-added effect (VA). For measuring domestic value added embodied in exports, existing literature has mainly used two approaches: one is macro-level measurement based on input-output tables; the other is micro-level measurement combining industrial enterprise database and customs data. Since the second approach focuses on individual firms and cannot satisfy industry heterogeneity analysis for the value-added effect, this paper follows existing studies and uses the ratio of manufacturing sector value added to manufacturing output. Data are sourced from the EORA input-output tables.

(3) Comprehensive technology effect (GTC□GEC). Following existing research[36], the GML index is used to decompose CEE into two sub-dimensions: GTC and GEC. GTC reflects the outward shift of the production frontier, representing progress driven by technological innovation; GEC reflects the degree of catch-up to the existing technology frontier, representing improvements in management efficiency. Using 2014 as the base year (set to 1), the cumulative multiplication method is applied to obtain the GTC and GEC levels for each country's manufacturing sector.

(4) Fixed asset investment (Inv). At the firm level, fixed asset investment is often measured as the ratio of cash paid for fixed assets, intangible assets, and other long-term assets to total assets at period end. Following this logic and drawing on previous input-output studies on the relationship between fixed assets and carbon productivity, this paper measures fixed asset investment as the ratio of manufacturing fixed asset investment to total input, with a depreciation rate of 9.6%. Data are sourced from EORA.

(5) Inventory (Stock). At the firm level, inventory is often measured using the logarithm of non-finished goods inventory. Due to data availability, a proxy variable is used at the manufacturing level. Existing research shows that manufacturing productivity is one of the determinants of inventory levels: higher productivity helps shorten the lead time for finished goods given fixed output, lowers desired safety stock, and thus maintains high inventory turnover. Therefore, this paper uses the inverse of manufacturing productivity measured by the super-efficiency SBM model excluding undesired outputs as a proxy for inventory. Specifically, the inventory variable is constructed as $\mathrm{Stock} = 1/\mathrm{productivity}$, ensuring that a higher value of the proxy corresponds to higher inventory levels, thereby maintaining consistent directional interpretation in the regression analysis. Data are sourced from the World Bank, EORA input-output tables, and the IEA.

(6) Onshore service outsourcing (OS). Among the quantification methods for outsourcing, the DJ index can be distinguished into broad and narrow categories. This study uses the broad DJ index to calculate the onshore outsourcing level of manufacturing, measuring domestic onshore service outsourcing. Based on existing literature practices[5], the share of domestic service inputs in manufacturing intermediate inputs is used. Data are sourced from the EORA input-output tables.

(7) Transaction cost (TC). At the firm level, transaction cost is often proxied by trade credit. At the manufacturing level, transaction cost can be measured in two ways: one is the input servitization approach, and the other is the market segmentation index based on relative prices. Since the relative prices of markets to which manufacturing sectors in different countries belong are difficult to determine, this paper follows existing input servitization practices and measures transaction cost as the ratio of service inputs from transportation, warehousing, and postal services to total manufacturing output. Data are sourced from the EORA input-output tables.

(8) Global value chain position (GVC). For quantifying the position in global value chains, existing research largely draws on the methodological frameworks proposed by Koopman et al. (2010) and Wang et al. (2013), which focus on characterizing the segment of a given economy within the global production chain. Following existing practices, this paper uses the approach of Wang et al.,

which considers upstreamness and downstreamness indices and ensures that production length does not vary with the number of industry classifications, measuring GVC relative upstreamness as the ratio of forward linkages to backward linkages. Data are sourced from the EORA input-output tables.

(9) External demand channel variable (ED). External demand variables are well established at the firm level, mainly using the shift-share method. At the manufacturing level, external demand is reflected in the exports of the domestic industry to foreign industries. To eliminate dimensional effects, this paper uses log-transformed and standardized manufacturing merchandise exports to represent domestic manufacturing external demand. Data are sourced from the World Bank.

4.2.4 Control variables

Referring to existing studies on manufacturing carbon emission efficiency [20], this paper controls the following country-level characteristic variables: (1) Foreign direct investment (Fdi), measured as the ratio of actual utilized foreign direct investment to GDP. FDI can promote technology spillovers and improve manufacturing energy processes, thereby enhancing manufacturing carbon emission efficiency. (2) Urbanization level (Urban), measured as the share of urban population in total population. Urban agglomeration can optimize resource allocation and reduce marginal carbon emissions, facilitating the formation of green scale effects in manufacturing. (3) Industrial structure (Ind), measured as the share of the tertiary sector in GDP. An increase in the tertiary sector's share can optimize the energy mix and thus improve carbon emission efficiency. (4) Trade dependence (Trade), measured as the ratio of total imports and exports to GDP. Trade dependence affects the domestic supply level of manufacturing and thereby moderates manufacturing carbon emission efficiency. (5) Government participation (Gov), measured as the share of general government final consumption expenditure in GDP. Governments can influence green technology promotion and environmental regulation through environmental policies, indirectly affecting manufacturing carbon emission efficiency. (6) Energy intensity (Ei), measured as the ratio of primary energy consumption to GDP. Energy intensity directly affects energy consumption efficiency and thereby determines the level of manufacturing carbon emissions. (7) Life expectancy (LE), measured as the average life expectancy of the population aged 15 and above in each country. An increase in life expectancy reflects improvements in national health levels and human capital accumulation, which help enhance the productivity and green technology absorption capacity of the manufacturing workforce. (8) ESG level of listed firms (ESG), measured as the average MSCI score of listed firms' ESG levels in each country. A higher ESG level can force manufacturing firms to increase green technology investment and energy optimization, thereby indirectly improving a country's carbon emission efficiency. ESG data for listed firms are sourced from the MSCI database, and other control variables are sourced from the World Bank.

Table 3
Descriptive Statistics

Variable name	Symbol	Dimension	Obs.	Mean	Std. dev.	Min	Max	VIF
Manufacturing carbon emission efficiency	CEE	Dependent	432	0.539	0.264	0.161	1.047	/
Manufacturing input servitization	Serin	Core explanatory	432	0.398	0.167	0.000	1.145	1.11
Manufacturing output servitization	Serout	Core explanatory	432	0.436	0.564	0.000	3.562	1.12
Foreign direct investment	Fdi	Control	432	0.046	0.087	-0.044	0.610	1.17
Urbanization level	Urban	Control	432	0.602	0.197	0.172	1.000	1.90
Industrial structure	Ind	Control	432	0.556	0.084	0.366	0.797	1.00
Trade dependence	Trade	Control	432	0.718	0.429	0.195	1.990	1.18
Government participation	Gov	Control	432	0.154	0.042	0.054	0.257	1.49
Energy intensity	Ei	Control	432	0.045	0.021	0.014	0.144	1.52
Life expectancy	LE	Control	432	73.504	6.475	59.539	83.498	1.24
ESG of listed firms	ESG	Control	432	2.766	2.097	0.000	7.000	1.25
Cost effect	Cost	Mechanism	432	0.898	1.282	-7.512	3.363	/
Value-added effect	VA	Mechanism	432	0.286	0.155	0.033	0.999	/
Green technology progress	GTC	Mechanism	432	1.032	0.149	0.560	1.588	/
Green technology efficiency	GEC	Mechanism	432	0.956	0.210	0.399	1.668	/
Fixed asset investment	Inv	Channel	432	0.426	0.265	0.082	1.804	/
Inventory	Stock	Channel	432	2.200	1.018	0.956	4.639	/
Service outsourcing	OS	Channel	432	0.272	0.182	-0.260	1.071	/
Transaction cost	TC	Channel	432	0.089	0.040	0.000	0.210	/
Global value chain position	GVC	Channel	432	-0.333	2.002	-4.842	5.984	/
External demand	ED	Channel	424	0.475	0.225	0.000	1.000	/

Note: Data are winsorized at the 1% level.

5. Empirical results and analysis

5.1. Descriptive Statistics

Descriptive statistics show that all data are winsorized at the 1% level to eliminate the influence of outliers (Table 3). The VIF values for all variables are below the critical level of 2, indicating no severe multicollinearity among the explanatory variables.

Figure 2 presents the scatter plots between manufacturing servitization and carbon emission efficiency. Overall, input servitization shows a clear negative linear relationship, while output servitization's negative effect is weaker. In low servitization regions, scatter points are dense with gentle slopes; in high regions, they are more dispersed, suggesting possible nonlinear marginal effects.

5.2. Benchmark model testing

5.2.1. Benchmark regression results

Table 4 reports the benchmark regression results. Columns (1)-(2) show that the Serin coefficient is significantly negative at 1%, remaining robust with controls. Columns (3)-(4) show the Serout coefficient is also significantly negative at 1%. These findings are consistent with Dong et al. (2020)[23], These findings align with Dong et al. (2020), suggesting that early-stage servitization accelerates service inputs for scale economies, increasing energy consumption and emissions. Similarly, excessive low-end output services intensify resource use, creating a "green cost.".

Current manufacturing servitization exhibits a significant inhibiting effect on carbon efficiency[1], failing to support Hypotheses 1a and 1b. However, the negative relationship suggests possible nonlinearity, tested subsequently.

Table 4
Estimation Results of the Impact of Manufacturing Servitization on Carbon Emission Efficiency

	(1)	(2)	(3)	(4)
	CEE	**CEE**	**CEE**	**CEE**
Serin	-0.320***	-0.330***		
	(-3.967)	(-4.109)		
Serout			-0.076**	-0.079***
			(-2.520)	(-2.765)
Control variables	No	Yes	No	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Constant	Included	Included	Included	Included
Observations	432	432	432	432
Adj.R2	0.910	0.918	0.902	0.910
Note: ***, **, and * denote significance at the 1%, 5%, and 10% significance levels, respectively; t-values are in parentheses.				

5.2.2. Robustness tests for the benchmark model

Table 5
Robustness Test Results for Manufacturing Input Servitization

	(1)Replace X1	(2)Change model	(3)Change years (2014–2019)	(4)Replace Y (single-factor)	(5)Replace Y (multi-factor)	(6)Winsorize 2%	(7)Expand sample (81 countries)	(8)System GMM
	CEE	CEE	CEE	CEE	CEE	CEE	CEE	CEE
Serin	-0.076***	-0.330***	-0.377***	0.001**	-0.296***	-0.530***	-0.193**	-0.129**
	(-5.493)	(-6.713)	(-4.282)	(2.002)	(-3.311)	(-5.703)	(-2.136)	(-2.461)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
L.CEE								0.721***
								(6.502)
AR(1)								0.004
AR(2)								0.120
Hansen test								0.456
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Included	Included	Included	Included	Included	Included	Included	Included
Observations	432	432	324	432	432	432	648	378
Adj.R2	0.913	0.918	0.918	0.735	0.954	0.921	0.888	/

Table 5 shows that after replacing the core variable, adjusting the model, shortening the sample to 2014–2019, replacing the dependent variable, and winsorizing at 2%, the Serin coefficient remains significantly negative. The single-factor carbon productivity measure shows the expected opposite sign, while the multi-factor ML index also yields a significantly negative coefficient. System GMM passes all tests, and extending the sample to 81 countries confirms robustness.

Table 6 confirms that output servitization coefficients remain significantly negative under the same robustness checks. Single-factor and multi-factor results are consistent, and system GMM passes all tests. Extending the sample to 81 countries further supports the findings.

Table 6
Robustness Test Results for Manufacturing Output Servitization

	(1)Replace X2	(2)Change model	(3)Change years (2014–2019)	(4)Replace Y (single-factor)	(5)Replace Y (multi-factor)	(6)Winsorize 2%	(7)Expand sample (81 countries)	(8)System GMM
	CEE	CEE	CEE	CEE	CEE	CEE	CEE	CEE
Serout	-0.040***	-0.079***	-0.087***	0.001***	-0.079*	-0.111***	-0.095*	-0.098***
	(-3.281)	(-3.155)	(-2.980)	(3.276)	(-1.943)	(-3.942)	(-1.720)	(-3.460)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
L.CEE								0.717***
								(5.151)
AR(1)								0.006
AR(2)								0.305
Hansen test								0.448
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Included	Included	Included	Included	Included	Included	Included	Included
Observations	432	432	324	432	432	432	648	378
Adj.R^2	0.909	0.910	0.907	0.758	0.953	0.911	0.887	/

5.2.3. Endogeneity test

In the endogeneity test for manufacturing input servitization (Serin) on carbon emission efficiency (CEE), following existing carbon emission efficiency studies, Instrumental Variable 1 (IV1) is measured as the logarithm of the average manufacturing input servitization of other countries in the sample period, excluding the home country. The rationale is that the overall manufacturing input servitization in the Belt and Road region affects the domestic servitization process but does not directly affect domestic manufacturing carbon emission efficiency, satisfying the relevance and exogeneity conditions. Following existing input servitization studies, IV2 is the one-period lagged manufacturing input servitization. For the endogeneity test of manufacturing output servitization (Serout) on CEE, IV3 and IV4 are selected analogously to IV1 and IV2: IV3 is measured as the logarithm of the average manufacturing output servitization of other countries in the sample period, excluding the home country, and IV4 is the one-period lagged manufacturing output servitization.

Table 7
Estimation Results of Instrumental Variable Method

	(1)First stage	(2)Second stage	(3)First stage	(4)Second stage
	CEE	CEE	CEE	CEE
IV1	-3.515***			
	(-3.11)			
IV2	0.493***			
	(4.66)			
Serin		-0.271***		
		(-2.42)		
IV3			-11.051***	
			(-30.96)	
IV4			0.143***	
			(2.94)	
Serout				-0.096***
				(-4.05)
K-P rk LM		12.970***		7.053**
		(0.0015)		(0.0294)
K-P rk Wald F		25.158		485.126
Overidentification test		0.6346		0.5289
Control variables	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Constant	Included	Included	Included	Included
Observations	378	378	378	378

Table 7 reports the instrumental variable (IV) estimation results to address potential endogeneity issues. The first-stage results show that for both manufacturing input servitization (Serin) and output servitization (Serout), the coefficients of the instruments (IV1, IV2, IV3, IV4) are significantly negative at the 1% level, indicating strong relevance between the instruments and the core explanatory variables. Second, the under-identification test (Kleibergen-Paap rk LM statistic) rejects the null hypothesis of "instruments are under-identified" at the 5% and 1% levels, respectively. The weak instrument test (Kleibergen-Paap rk Wald F statistic) is far above the Stock-Yogo critical value of 19.93 (for 10% bias with two instruments), ruling out the weak instrument problem. The over-identification test p-values are greater than 0.1 in all cases, indicating that the instruments satisfy the exogeneity condition-they affect the dependent variable only through the endogenous variables. The second-stage results show that after controlling for potential endogeneity, the estimated coefficients of input servitization and output servitization are − 0.271 and − 0.096, respectively, both significant at the 1% level. These results are consistent with the benchmark regression, confirming the conclusion that current servitization has not yet significantly improved manufacturing carbon emission efficiency.

5.3. mediation effect test

5.3.1. Mechanism tests

Table 8 reports the results of the mechanism tests. For the cost effect, Column (1) shows that the coefficient of Serin on Cost is 1.095, significant at the 1% level, indicating that manufacturing input servitization significantly increases intermediate costs in the

sample countries. This confirms the mediation transmission of the cost effect in Hypothesis 2a, but the specific direction is "increasing costs – suppressing carbon efficiency." This finding is consistent with Dong et al. (2021)[29], who observed that early-stage industrial convergence increases coordination costs, crowds out energy dependence, and hinders green innovation effectiveness. In Column (2), the coefficient of the interaction term (Cost×Serin) is -0.120, significant at the 5% level, indicating that input servitization exacerbates the negative impact of the cost effect on carbon efficiency. Based on the mediation effect calculation, under the average level of input servitization over 2014–2021, the indirect effect coefficient is 1.095 × [-0.094 + (-0.120) × 0.398] = -0.155. Combined with the direct effect coefficient of -0.151, the indirect effect accounts for approximately 50.7% (|-0.155| / (|-0.155| + |-0.151|)), making it the main transmission mechanism through which input servitization affects carbon emission efficiency.

For the value-added effect, Column (3) shows that the coefficient of output servitization on the value-added effect is -0.056, significant at the 1% level, indicating that the transformation has not yet effectively enhanced value-added capture. In Column (4), the coefficient of the interaction term (VA×Serout) is 0.778, significant at the 1% level and positive, indicating that an increase in the value-added effect strengthens the emission reduction effect of output servitization. The mediation effect accounts for approximately 39.0% under the average level of output servitization. Hypothesis 2b-that the value-added effect is a mediating mechanism-is confirmed in terms of direction, but there is a clear transmission blockage at the current stage. This result contrasts with Tang et al. (2022)[19], who found that input servitization itself has a carbon reduction effect, which is offset by global value chain participation. The present study suggests instead that output servitization has not only failed to increase value added but has actually solidified a low-value-added structure due to excessive concentration on low-end after-sales services, thereby eroding the potential for carbon reduction. Finally, Column (5) of Table 8 verifies a certain synergy between input servitization and output servitization.

Table 8
Mechanism Analysis: Manufacturing Servitization

	(1)	(2)	(3)	(4)	(5)
	Cost	**CEE**	**VA**	**CEE**	$Serout$
$Serin$	**1.095****	-0.151**	**-0.056*****		0.871**
	(2.279)	(-2.165)	**(-5.488)**		(2.490)
$Serout$				0.139***	
				(3.755)	
$\text{Cost} \times Serin$		**-0.120****			
		(-2.309)			
Cost		-0.094***			
		(-4.289)			
$VA \times Serout$				**0.778*****	
				(5.512)	
VA				1.248***	
				(10.092)	
Control variables	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes
Constant	Included	Included	Included	Included	Included
Observations	432	432	432	432	432
Adj.R^2	0.892	0.927	0.952	0.941	0.929

For technology effect, input servitization inhibits GEC, but the interaction is not significant, suggesting a direct effect. Output servitization also inhibits GEC, and the interaction (GEC×Serout) is positive (0.314), with an indirect effect accounting for 32.1%. Effects on GTC are insignificant (not reported).

Table 8
(Continued) Mechanism Analysis: Manufacturing Servitization

	(6)	(7)	(8)	(9)
	GEC	**CEE**	**GEC**	**CEE**
$Serin$	-0.337***	-0.201***		
	(-2.973)	(-3.629)		
$GEC \times Serin$				
$Serout$			-0.069*	0.072
			(-1.777)	(1.398)
GEC		0.312***		0.358***
		(6.846)		(7.641)
$\mathrm{GEC} \times Serout$		**0.163**		**0.314*** **
		(1.428)		**(3.146)**
Control variables	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Constant	Included	Included	Included	Included
Observations	432	432	432	432
Adj. R^2	0.691	0.937	0.677	0.937

5.3.2. Channel tests

Table 9 reveals the specific transmission pathways through which servitization affects carbon efficiency from both cost and supply-demand sides. For input servitization, its coefficient on fixed asset investment (Inv) is 0.123, significant at the 1% level, indicating that the early stage of transformation is still characterized by heavy capital deepening. This suggests that the introduction of service factors has not yet brought about the asset-light green effect expected by Xia and Zhou (2024)[3], who argued that transportation and warehousing servitization can significantly reduce SO_2 emissions. This may be because such services themselves still rely heavily on transport equipment and facilities, and the current Belt and Road countries have not yet achieved a reasonable substitution of service factors. More revealing are the two channels of inventory and transaction costs: the coefficient of input servitization on the inventory proxy (Stock) is 0.914 (significant at the 5% level). Because Stock is constructed as the inverse of productivity, a positive coefficient directly indicates that servitization leads to higher inventory accumulation, which in turn suppresses carbon emission efficiency. Meanwhile, the coefficient on the transaction cost channel (TC) is 0.146 (significant at the 1% level), reflecting that the expansion of service procurement significantly increases coordination and contracting costs. Although the coefficient on service outsourcing (Outsource) is positive and significant (0.998), as expected, indicating a clear trend toward externalizing non-core activities, the triple pressures of difficulty in asset-light investment, inventory efficiency loss, and rising transaction costs constitute the core blockage through which input servitization suppresses carbon efficiency.

Table 9
Indirect Pathway Analysis by Channel

	(1)	(2)	(3)	(4)	(5)	(6)
	Manufacturing soft and hard cost dimensions				**Manufacturing supply-demand aspects**	
	Fixed asset investment (Inv)	Inventory (Stock)	Service outsourcing (Outsource)	Transaction cost (TC)	Global value chain position (GVC)	External demand (ED)
Serin	0.123***	0.914**	0.994***	0.146***		
	(5.275)	(2.090)	(26.481)	(9.244)		
Serout					-0.388*	0.006
					(-1.798)	(1.589)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Bootstrap (1000)	**0.123(0.027) [0.069, 0.176]**	**0.914 (0.054) [-0.014, 1.843]**	**0.994 (0.038) [0.918, 1.070]**	**0.146 (0.018) [0.110, 0.181]**	/	/
Constant	Included	Included	Included	Included	Included	Included
Observations	432	432	432	432	432	432
Adj.R^2	0.971	0.946	0.980	0.963	0.909	0.994

The channel test results for output servitization are also noteworthy. Its coefficient on global value chain position (GVC) is -0.388, significant at the 10% level and negative, indicating that output servitization in the current partner countries has not yet effectively promoted value chain upgrading. This is because, under the “pollution haven hypothesis,” participation in GVCs is detrimental to the carbon reduction effect of servitization[19] and may even reinforce the existing low-end pollution-intensive division of labor. The coefficient on the external demand channel (ED) is only 0.006 and not significant, which contradicts previous studies[37] that found servitization improves export product quality. This suggests that the scale-pulling effect of output servitization on external demand is limited. Overall, hindered GVC upgrading is a key transmission channel for the carbon efficiency loss caused by output servitization.

5.4. Heterogeneity Analysis

5.4.1. Heterogeneity in input service quality

The main obstacles to the integration of manufacturing and services are the small scale and low quality of high-tech services[29]; low-quality services may inhibit manufacturing productivity due to Baumol’s cost disease. Existing research has pointed out that high-quality services characterized by the accumulation of knowledge and human capital are conducive to improving efficiency. Therefore, manufacturing servitization needs to pay attention to the quality of input services. When a country’s share of knowledge- and technology-intensive producer services in total input is larger-meaning more high-quality service inputs-the positive effects such as substitution of traditional energy and optimization of production processes become more significant, and correspondingly, the improvement in carbon emission efficiency becomes stronger.

Table 10
Heterogeneity Analysis Results

	Heterogeneity in Knowledge and Technology Intensive Inputs
	(1)CEE
KT×$Serin$	**0.776*** **
	(3.874)
$Serin$	-0.567***
	(-6.828)
Share of knowledge and technology intensive inputs	0.103
(KT)	(1.514)
Control variables	Yes
Time FE	Yes
Country FE	Yes
Constant	Included
Observations	432
Adj.R^2	0.922

Column (1) of Table 10 reports the estimation results of the interaction term between the share of knowledge- and technology-intensive service inputs (KT) and input servitization (Serin), aiming to test the heterogeneity effect of input service quality. To test the above expectation, this paper measures input service quality as the share of knowledge and technology intensive service inputs[2] in total service inputs and includes its interaction term with input servitization (Serin) in the regression model. Column (1) shows that the coefficient of the interaction term (KT × Serin) is significantly positive at 0.776, revealing that as the proportion of knowledge- and technology-intensive service inputs increases, the negative impact of input servitization on carbon emission efficiency is significantly mitigated.

5.4.2. Heterogeneity in manufacturing value-added structure

The value-added rate of manufacturing reflects the value creation capacity and position in the global value chain. Low-value-added manufacturing typically relies on high-energy-consuming processes, with carbon intensity much higher than that of high-tech industries. In contrast, high-value-added manufacturing concentrates on low-carbon, high-value-added activities such as R&D, design, and branding, and servitization can more easily spread emission reduction costs through scale effects. Therefore, the larger the share of high-value-added manufacturing in total output, the more significant the carbon emission reduction effect of output servitization.

Table 10
(Continued) Heterogeneity Analysis Results

	Low-value-added manufacturing heterogeneity	**High-value-added manufacturing heterogeneity**
	(2)	**(3)**
	CEE	**CEE**
$Serout \times$low_group	**-0.077*** **	
	(-2.950)	
low_group	-0.045**	
	(-2.381)	
$Serout$	-0.007	-0.085***
	(-0.262)	(-4.118)
$Serout \times$ high_group		**0.077*** **
		(2.950)
high_group		0.045**
		(2.381)
Control variables	Yes	Yes
Time FE	Yes	Yes
Country FE	Yes	Yes
Constant	Included	Included
Observations	432	432
Adj.R^2	0.922	0.922

Columns (2) and (3) of Table 10 report the estimation results of the interaction terms with output servitization (Serout), testing the heterogeneity effect of manufacturing value-added structure. To test the above scenario analysis, this paper divides the sample into two groups-high and low manufacturing value added-using the sample mean as the cutoff. A low-value-added group dummy variable (low_group) and a high-value-added group dummy variable (high_group) are introduced, and their interaction terms with output servitization (Serout) are tested. The results show that the coefficient of Serout × low_group is -0.077 ($p < 0.01$), and the coefficient of Serout × high_group is 0.077 ($p < 0.01$), indicating that the inhibiting effect of output servitization on carbon emission efficiency is stronger in countries with low-value-added manufacturing compared with those with high-value-added manufacturing.

The between-group T-test confirms the validity of the grouping (Table 11).

Table 11
T-test for Between-Group Differences

Variable	**High-value-added group (N = 177)**	**Low-value-added group (N = 255)**	**Mean difference**	**T-statistic**
VA	0.402	0.206	0.195***	14.12

5.4.3. Heterogeneity in country income level

Countries at different income levels differ significantly in technological innovation capacity, environmental regulation intensity, and industrial structure. To test income-level heterogeneity, Table 12 divides the sample countries into four groups (high-income, upper-

middle-income, lower-middle-income, and low-income) according to the World Bank income classification and performs group regressions.

Table 12
Estimation Results of Heterogeneity Analysis by Country Income Level

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	High income	**Upper-middle income**	**Lower-middle income**	**Low income**	**High income**	**Upper-middle income**	**Lower-middle income**	**Low income**
$Serin$×Di	-0.210*	-0.530***	-0.330***	2.059***				
	(-1.744)	(-6.949)	(-2.765)	(2.884)				
$(Serout \times \mathrm{Di})$					-0.076	-0.087***	0.002	0.751
					(-1.091)	(-2.706)	(0.027)	(0.453)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Included	Included	Included	Included	Included	Included	Included	Included
Observations	432	432	432	432	432	432	432	432
Adj.R^2	0.909	0.918	0.909	0.910	0.907	0.909	0.907	0.907

For input servitization (Serin), the coefficients are significantly negative in high-income, upper-middle-income, and lower-middle-income countries, with the absolute value first increasing and then decreasing. This indicates that input servitization generally suppresses carbon emission efficiency in these economies. Among them, the negative effect is most pronounced in upper-middle-income countries. The reason is that this group is in the middle-to-late stage of industrialization, with a large manufacturing scale but an energy structure that has not yet completed low-carbon transformation. The introduction of service factors exacerbates intermediate costs and inventory pressures in the short term. Notably, in the low-income country group, the coefficient of Serin is significantly positive at 2.059 (1% level). A possible explanation is that when service inputs increase from very low levels, even the most basic logistics and trade services can significantly improve production efficiency and energy utilization, thereby enhancing carbon emission efficiency.

For output servitization (Serout), only the coefficient for upper-middle-income countries is significantly negative (-0.087 at the 1% level); the coefficients for the other income groups are not statistically significant. This indicates that the inhibiting effect of output servitization on carbon emission efficiency is concentrated mainly in upper-middle-income countries. The reason is that upper-middle-income countries are often the main hosts of processing and manufacturing activities in global value chains. Manufacturing output servitization in these countries is mainly reflected in low-end services such as after-sales support and transportation supporting products, and has not yet achieved an upgrade to high-value-added activities such as R&D and branding. This low-end output servitization increases carbon emissions from service activities without generating corresponding value-added growth, thus exhibiting significant carbon efficiency losses. In contrast, high-income countries have entered the post-industrial stage, where output servitization is more focused on knowledge-intensive and digital services, and the associated negative environmental effects are relatively small.

5.5. Further Analysis

5.5.1. Nonlinear test of manufacturing servitization on carbon emission efficiency

To examine the possible nonlinear relationship between manufacturing servitization and carbon emission efficiency, this paper introduces quadratic terms of the servitization variables into the benchmark model; the results are reported in Table 13. Column (1) shows that the coefficient of the linear term of input servitization (Serin) is significantly negative (-0.559, 1% level), while the coefficient of the quadratic term (Serin²) is significantly positive (0.478, 1% level), indicating a U-shaped relationship between input servitization and carbon emission efficiency. In the early stage of transformation, cost pressures and adaptation frictions from embedding service factors dominate, and carbon efficiency declines as servitization increases. After servitization crosses a certain threshold, the factor substitution and process optimization effects gradually unfold, and carbon efficiency begins to rise. Column (2) shows that output servitization (Serout) also exhibits a significant U-shaped relationship: the linear term coefficient is -0.218 ($p < 0.01$), and the quadratic term coefficient is 0.050 ($p < 0.05$). This indicates that output servitization also has a “first inhibit then promote” nonlinear characteristic. These results respond to the expectations of nonlinear relationships in Hypotheses 1a and 1b and are similar to Li et al. (2024)[25], who found a U-shaped effect of servitization on firm performance in Chinese sporting goods manufacturing enterprises, verifying the empirical regularity that the early stage of servitization transformation is accompanied by a phased “green cost”.

Table 13
Nonlinear Results of the Impact of Manufacturing Servitization on Manufacturing Carbon Emission Efficiency

	(1)	**(2)**
	CEE	**CEE**
$Serin$	-0.559***	
	(-5.675)	
$Serin^2$	**0.478*** **	
	(3.103)	
$Serout$		-0.218***
		(-3.088)
$Serout^2$		**0.050** **
		(1.997)
Control variables	Yes	Yes
Time FE	Yes	Yes
Country FE	Yes	Yes
Constant	Included	Included
N	432	432
Adj. R^2	0.921	0.912
Note: Interaction terms and their components have been centered.		

6. Conclusion and suggestions

6.1. Research conclusions

Based on manufacturing panel data of 54 Belt and Road partner countries from 2014 to 2021, with manufacturing input and output servitization as the core explanatory variables, and using the super-efficiency SBM-GML model, panel fixed effects models, and

mediation effect models, this paper systematically examines the impact of manufacturing servitization on carbon emission efficiency. The main conclusions are as follows:

First, the impact of manufacturing servitization on carbon emission efficiency exhibits the characteristics of a “transformation pain” period, and there is a significant U-shaped nonlinear relationship between the two. Benchmark regressions show that both input and output servitization have a significant inhibiting effect on carbon emission efficiency. Nonlinear tests confirm that the early stage of servitization transformation is accompanied by a phased “green cost.” This study reveals the dynamic pattern of environmental effects during servitization transformation: simply promoting servitization does not necessarily bring short-term improvements in carbon efficiency; the green dividend can only be realized after crossing a specific threshold.

Second, the cost effect and the value-added effect are the core mechanisms, but there are clear transmission blockages. Input servitization significantly increases intermediate costs through channels such as increasing fixed asset investment, exacerbating inventory accumulation, and raising transaction costs, thereby indirectly suppressing carbon efficiency improvement, with a mediation effect of approximately 50.7%. Output servitization weakens sectoral value-added capture by inhibiting global value chain positioning, with a mediation effect of approximately 39.0%. In addition, regarding the technology effect, output servitization significantly inhibits green technology efficiency, with a mediation effect of approximately 32.1%, confirming that the loss in green technology management and application efficiency is concentrated on the output side.

Third, the environmental effects of servitization are conditional on factor endowment structure, manufacturing industry characteristics, and country income level heterogeneity. Specifically: a higher share of knowledge- and technology-intensive service inputs significantly mitigates the negative impact of input servitization on carbon emission efficiency. In economies with a higher share of high-value-added manufacturing, output servitization is more beneficial to carbon efficiency improvement. From the income level perspective, input servitization exhibits the most pronounced negative effect in upper-middle-income countries, but shows a positive promoting effect in low-income countries. Output servitization only shows a significant inhibiting effect in upper-middle-income countries.

6.2. Policy suggestions

Based on the above findings, to promote the green and low-carbon transformation of manufacturing in Belt and Road partner countries and achieve synergistic improvement between servitization and carbon efficiency, the following policy suggestions are proposed:

1. Promote quality upgrading of manufacturing servitization. Countries should adopt industrial guidance and fiscal policies to encourage manufacturing firms to prioritize the procurement of high-value-added green producer services such as R&D design, digital solutions, and energy management, gradually replacing traditional low-efficiency service inputs. At the same time, a green service innovation fund should be established to support third-party service providers in developing energy-saving and emission-reduction solutions with scale and network effects, thereby reducing the marginal cost for firms to adopt green services. To address the heavy-asset problem exposed during input servitization, manufacturing firms should be encouraged to adopt equipment leasing and outsource non-core production activities, promoting the formation of asset-light operations. To address inventory pressures, cloud-based smart warehousing technologies should be actively promoted, using big data to optimize production scheduling and inventory turnover, thereby reducing embodied carbon emissions in warehousing. To address high transaction costs, an information-sharing platform between manufacturing and service sectors should be established to facilitate precise matching of supply and demand, reducing information asymmetry and transaction costs. Regarding the impact of output servitization on domestic manufacturing GVC positions, a “Green Value Chain Partnership Program” should be implemented to support leading manufacturing firms in forming industry innovation alliances with universities, research institutions, and green service providers, jointly tackling core low-carbon technologies and promoting the transformation toward more advanced “product + service” solutions, so that servitization truly achieves dual improvements in economic and environmental benefits.
2. Implement differentiated international green manufacturing cooperation. Belt and Road partner countries vary considerably in manufacturing development levels, as well as in starting points and demands for green transformation. Therefore, international green manufacturing cooperation must adopt differentiated strategies and targeted alignment. For countries with a strong technological and industrial base, cross-border cooperation should shift toward joint R&D of high-end green intelligent manufacturing technologies, co-innovation of green service business models, and the establishment of regional green service

centers for manufacturing. Through knowledge sharing and technology spillovers, these efforts can jointly lead the construction of global green value chains and create demonstration effects in high-end areas. For countries in the middle stages of industrialization with a high proportion of traditional industries, cooperation should focus on the transfer and adaptation of applicable green technologies, systematic training in environmental skills, and the construction of green infrastructure. The “advanced technology + localized services + capacity building” model should be used to help their traditional industries complete low-carbon transformation during servitization upgrading, avoiding the “high-carbon lock-in” trap. Upper-middle-income countries should focus on introducing knowledge- and technology-intensive services to break high-carbon lock-in, while low-income countries should start with basic logistics and digital infrastructure to achieve a leapfrog green start. Through these differentiated international servitization cooperation strategies, regional manufacturing carbon emission efficiency can be improved holistically, achieving mutual benefits under the Green Silk Road initiative.

3. Expand green scenario applications of the Digital Silk Road. Leveraging cross-border data flows and digital infrastructure connectivity under the Digital Silk Road framework, a big data collaborative platform for carbon efficiency should be established covering manufacturing servitization in Belt and Road partner countries. Multi-agent systems, deep reinforcement learning, and other artificial intelligence algorithms should be actively promoted to train regionally adapted U-shaped curve prediction models, accurately identifying the servitization transformation stage and green turning point thresholds for each country. For countries or industries in the “green cost” period of servitization, targeted delivery of efficient emission reduction technology solutions and service upgrading pathways should be provided through the Digital Silk Road online technology library, complemented by digital twin virtual simulation environments for rehearsal, reducing the cost of on-site trial and error. At the same time, a blockchain-based cross-border carbon efficiency early warning and tiered response mechanism should be established, forming a full-chain management system of “intelligent diagnosis – green leap fund fast track – cross-border expert remote assistance,” effectively shortening the pain period of green transformation in regional manufacturing as a whole. Finally, China’s first-mover advantages in new energy, digital technology, and green infrastructure should be fully utilized to assist enterprises in partner countries in connecting with international green supply chains and low-carbon markets, comprehensively enhancing their capacity to meet international environmental standards, and promoting the sustainable and robust development of green servitization of manufacturing along the Belt and Road.

6.3. Limitations and future research directions

Due to data availability, this study has certain limitations that need to be addressed in future research. First, the timeliness of the research sample needs to be improved. The data only extend to 2021 and do not fully reflect the impact of post-pandemic global supply chain restructuring and the accelerated implementation of carbon neutrality policies in various countries. Future research should extend the time span and pay attention to the latest policy shocks. Second, the micro-foundations of the impact mechanisms need to be deepened. The behavioral logic of firms’ strategic choices and organizational changes is not examined. Future research could use firm survey data or case study methods to conduct in-depth analyses.

Declarations

Author Contribution

Author A. (First Author): Conceptualization, Methodology, Formal analysis, Writing – Original Draft, Funding acquisition.Author B. (Co-author): Supervision, Validation, Visualization, Writing – Review & Editing.Author C. (Corresponding Author): Data curation Conceptualization, Software, Project administration, Writing – Review & Editing.All authors reviewed the manuscript.

Acknowledgement

The authors gratefully acknowledge financial support from the National Social Science Foundation of China (Grant No. 22XJY005) .We thank Prof. Linghu Dazhi for his guidance in the early stages of this research.

Data Availability

All data supporting the findings of this study are available within the paper and its Supplementary Information.

References

1. GAO P, YUE S J, CHEN H T (2021) Carbon emission efficiency of China's industry sectors: From the perspective of embodied carbon emissions[J]. JOURNAL OF CLEANER PRODUCTION, p 283
2. SHUANGJIE L, WEI W HONGYU D, Measuring the Efficiency of Energy and Carbon Emissions: A Review of Definitions, Models, and Input-Output Variables[J]. Energies,2022,15(3):962
3. XIA Q, ZHOU Z B (2024) Research on the impact of manufacturing servitization on environmental pollution: spatial econometric analysis of sulfur dioxide based on 284 prefecture-level cities[J], vol 22. CHINESE JOURNAL OF POPULATION RESOURCES AND ENVIRONMENT, pp 258–267. 3
4. CHEN FL, CHEN X Mitigating pollution emissions of manufacturing firms: Does input servitization matter? Empirical evidence from China[J]. ENERGY,2025,320.
5. ZHANG JY, SUN ZL (2025) Does the synergy between fintech and green finance lead to the enhancement of urban green total factor energy efficiency? Empirical evidence from China[J]. JOURNAL OF ENVIRONMENTAL MANAGEMENT, p 382
6. ZHAO D, CHEN J (2021) An analysis of the impact of service inputs in manufacturing industries on eco-efficiency: evidence from China[J], vol 28. ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH, pp 61825–61840. 43
7. ZHANG L N, ZHAO W C, CHIIU Y H et al Deep mitigation for trade-embodied carbon emissions among the Belt and Road Initiative countries[J]. ISCIENCE,2024,27(8).
8. LIU H, ZHU Y (2026) Input–output efficiency evaluation with undesirable outputs: An approach based on uncertain SBM-DEA model[J]. Comput Ind Eng 216:111965
9. ZHAO X Q, ZENG B Y, ZHAO X S et al (2024) Impact of green finance on green energy efficiency: A pathway to sustainable development in China[J]. JOURNAL OF CLEANER PRODUCTION, p 450
10. LIN B Q, GUAN C X Evaluation and determinants of total unified efficiency of China's manufacturing sector under the carbon neutrality target[J]. ENERGY ECONOMICS,2023,119.
11. YUAN HUS, WANG Z A L. Improving carbon emission efficiency in Chinese manufacturing: A study considering technological heterogeneity and noise[J]. ENERGY,2024,291.
12. LIU X P, ZHANG X L, SUN W Does the agglomeration of urban producer services promote carbon efficiency of manufacturing industry?[J]. LAND USE POLICY,2022,120.
13. LI JX, CHENG Z H (2020) Study on total-factor carbon emission efficiency of China's manufacturing industry when considering technology heterogeneity[J]. JOURNAL OF CLEANER PRODUCTION, p 260
14. WANG Y, DENG X Z, ZHANG H W et al (2022) Energy endowment, environmental regulation, and energy efficiency: Evidence from China[J]. TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE, p 177
15. PAN X F, LI M N, WANG MY et al The effects of outward foreign direct investment and reverse technology spillover on China's carbon productivity[J]. ENERGY POLICY,2020,145.
16. BIN H, LIU F, ZHENG YL et al Enhancing Carbon Emission Efficiency through the Integration of Two Industries: A Measurement Based on an Evaluation Index System[J]. SYSTEMS,2023,11(10)
17. WANG JL, WANG W L, WU H T et al Exploring the effects of manufacturing servitization on enterprise energy conservation and emissions reduction moderated by digital transformation[J]. ENERGY ECONOMICS,2023,122.
18. ZHANG JN, SUN X H, YUAN F et al Which type of servitization promotes firm performance: Embedded or hybrid?[J]. ECONOMIC MODELLING,2023,126.
19. TANG Y D, ZHU S J, LUO Y et al Input servitization, global value chain, and carbon mitigation: An input-output perspective of global manufacturing industry[J]. ECONOMIC MODELLING,2022,117.
20. YU H C, ZHANG Y G ZHUL (2024) The impact of collaborative agglomeration of manufacturing and services on carbon emission efficiency: spatial effect and mechanism analysis[J]. INTERNATIONAL JOURNAL OF SUSTAINABLE DEVELOPMENT AND WORLD ECOLOGY
21. XIAO Y T, XU Y L, LI M et al (2024) Does the integration of manufacturing and producer services improve carbon emission efficiency?[J], vol 26. CLEAN TECHNOLOGIES AND ENVIRONMENTAL POLICY, pp 1603–1619. 5

22. WANG HS, HE D N. CAN MANUFACTURING OUTPUT SERVITIZATION, REDUCE CARBON EMISSIONS?[J] (2023). INTERNATIONAL JOURNAL OF INDUSTRIAL ENGINEERING-THEORY APPLICATIONS AND PRACTICE,30(2):421–434
23. DONG F, WANG Y (2020) ZHENG L, et al. Can industrial agglomeration promote pollution agglomeration? Evidence from China[J]. JOURNAL OF CLEANER PRODUCTION, p 246
24. KE H Q, DAI S Z, YU HC (2022) Effect of green innovation efficiency on ecological footprint in 283 Chinese Cities from 2008 to 2018[J], vol 24. ENVIRONMENT DEVELOPMENT AND SUSTAINABILITY, pp 2841–2860. 2
25. LI H, LU L B, YANG S X Servitization level, digital transformation, and enterprise performance of sporting goods manufacturing enterprises in China[J]. HELIYON,2024,10(13).
26. HU Y H, SUN S, JIANG M et al Research on the promoting effect of servitization on export technological sophistication of manufacturing enterprises[J]. PLOS ONE,2021,16(8).
27. WU Q, CHEN Y H, WANG AX Decarbonizing global value chains: the dual role of manufacturing servitization in export-implied carbon emissions - scale expansion vs. structural upgrading[J]. MITIGATION AND ADAPTATION STRATEGIES FOR GLOBAL CHANGE,2026,31(2)
28. YUAN K H, WANG K R FEIRL et al (2023) The impact of manufacturing servitization on consumption-based carbon rebound effect: A global value chain research perspective[J]. SCIENCE OF THE TOTAL ENVIRONMENT, p 896
29. DONG F, LI Y F QINC et al (2021) How industrial convergence affects regional green development efficiency: A spatial conditional process analysis[J]. JOURNAL OF ENVIRONMENTAL MANAGEMENT, p 300
30. HU H, XIE N (2018) The role of renewable energy consumption and commercial services trade in carbon dioxide reduction: Evidence from 25 developing countries[J]. Appl Energy 211:1229–1244
31. HAO M R, TANG Y D, ZHU SJ (2022) Effect of input servitization on carbon mitigation: evidence from China's manufacturing industry[J], vol 29. ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH, pp 27819–27831. 19
32. DONG F, LI Y F, ZHANG X Y et al (2021) How does industrial convergence affect the energy efficiency of manufacturing in newly industrialized countries? Fresh evidence from China[J]. JOURNAL OF CLEANER PRODUCTION, p 316
33. ZONG Y, GU GD (2022) The threshold effect of manufacturing Servitization on carbon emission: An empirical analysis based on multinational panel data[J], vol 60. STRUCTURAL CHANGE AND ECONOMIC DYNAMICS, pp 353–364
34. SUI X N, HU H H, WANG HJ et al The impact of servitization transformation on the ESG performance of manufacturing firms[J]. INTERNATIONAL REVIEW OF ECONOMICS & FINANCE,2024,96.
35. CHANG Y, MING X G, ZHANG X Y et al Servitization and Sustainable Value Creation Strategy for China's Manufacturing Industry: A Multiple Case Study in the Belt and Road Initiative[J]. SUSTAINABILITY,2021,13(20).
36. MA ML, YANG Y F, MA Y Y et al Evaluation and heterogeneity of the green total factor productivity of Shandong Province, China: a super-SBM and GML analysis[J]. SCIENTIFIC REPORTS,2025,15(1).
37. SHI JM, LI J, WU JY et al Manufacturing servitization and export quality upgrading: evidence from China's multi-product exporters[J]. HUMANITIES & SOCIAL SCIENCES COMMUNICATIONS,2025,12(1).

Footnotes

1. All regressions in this paper control for country and year two-way fixed effects and employ heteroskedasticity-robust standard errors.
2. The specific categories of knowledge and technology service inputs, referencing studies on input servitization and the classification of multi-regional input-output industries, specifically select three sectors from the EORA input-output framework: post and telecommunications, financial intermediation and business services, and education, health and other services.

Figures

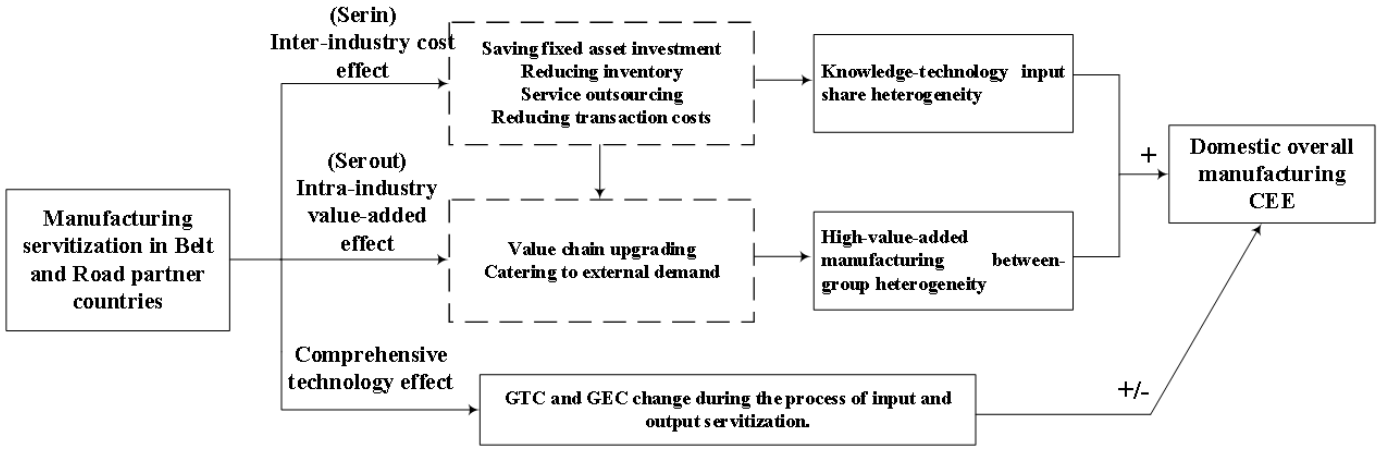


Figure 1

Mechanism of Manufacturing Servitization Affecting Carbon Emission Efficiency

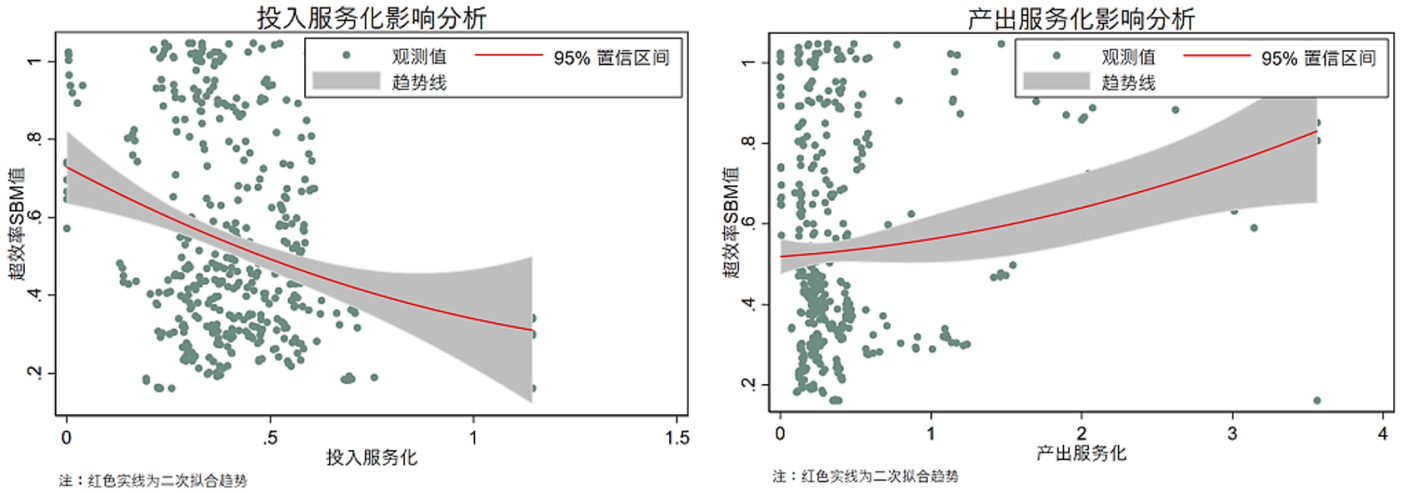


Figure 2

Scatter Plot of Sample Data

Supplementary Files

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