Mechanism of Digital Technology Enabling the Development of Port Logistics: A Case Study of Coastal Port Clusters in Southwest China

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Abstract. Digital technology has injected new momentum into the development of the logistics industry. Drawing on panel data related to six major ports and their host cities in the coastal port clusters of southwest China from 2005 to 2022, this article employs a dual fixed-effects model, mediation effect model, and threshold regression model to explore the internal mechanisms of digital technology in driving the development of port logistics. The results indicate that digital technology can effectively promote the development of port logistics. Additionally, digital technology significantly enhances port logistics levels by optimizing industrial structures and attracting foreign investment. Furthermore, a single threshold effect exists in the process of digital technology supporting the development of port logistics, with higher levels of digital technology development exerting stronger promotional effects on port logistics development.

Keywords: Port Logistics, Digital Technology, Coastal Port Clusters in Southwest China

1 INTRODUCTION

In recent years, with the development of global economic and production trade among various countries, ports, as nodes connecting land and sea, have gradually become hubs for global resource allocation and windows for opening up[1].Trade among countries mainly relies on shipping, and port logistics has become the world's primary mode of trade transportation due to its low-cost and high-efficiency transportation services. In 2020, China signed the Regional Comprehensive Economic Partnership (RCEP) agreement with fourteen other countries, which officially took effect in 2022. The implementation of RCEP is conducive to promoting the coordinated linkage of industrial and supply chain markets between China's southwestern coastal areas and RCEP member states. As one of China's five major port clusters, the southwestern coastal port cluster serves as an international gateway facing ASEAN. To facilitate the development of foreign trade in southwestern coastal areas, it is essential to promote resource coordination in port logistics, enhance the efficient operation of shipping logistics networks.

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In November 2023, General Secretary Xi Jinping proposed the innovative concept of "new-type productive forces," essentially referring to a new type of productive format driven primarily by cutting-edge technological innovation. Digital technology, as the core technology of new-type productive forces, can penetrate digital information into various fields of production and service, enhancing social production efficiency[2]. To leverage the characteristics of digital technology in accelerating industrial digital transformation, it is imperative to invest advanced information technology into the construction of port logistics industries. Therefore, taking the southwestern coastal port cluster as an example, this paper explores the internal mechanisms of digital technology in promoting port logistics development, aiming to provide theoretical references and suggestions for further accelerating the construction of China's new-type productive forces and enhancing the development level of port logistics.

2 LITERATURE REVIEW

Digital technology is the foundation and core driving force of the digital economy, including new-generation information technologies for example big data, block chain, the Internet of Things, artificial intelligence and cloud computing. With the increasing penetration of digital technology in industrial development, related research is also gradually increasing. For example, Zawawi et al. [3] pointed out that digital technology can directly improve the flexibility and efficiency of logistics processes, He[4] proposed that the wide application of digital technology plays a positive role in promoting the high-quality development of the logistics industry, Lu[5] studied the influence of digital technology applied in different production stages of manufacturing industry is studied on logistics and trade costs.

In the field of port logistics, many scholars have discussed the relationship between digital technology and port logistics. Gou et al. [6] pointed out that digital logistics can provide real-time logistics information and improve port logistics efficiency, Chen et al. [7]believed that using digital technology to innovate the business model of port logistics can provide more efficient logistics and transportation services, Cong[8]proposed that managing the port logistics chain with the help of digital technology can help reduce the transportation cost of port logistics .

In summary, many research conducted by digital technology and the relationship between the port logistics, but most of them are researched on a national or single city level, rarely on a certain region, and most of the research stays at the theoretical level, which needs to be supplemented by empirical analysis. Based on this, this paper takes the main ports of China's southwest coastal port group as an example, a dual fixed-effects model, mediation effect model, and threshold regression model to analyze the impact mechanism of digital technology on port logistics.

3 MECHANISM OF ACTION AND RESEARCH HYPOTHESIS

3.1 Digital Technology Has a Direct Impact on the Development of Port Logistics

Digital technology, using modern networks as a carrier, strengthens industrial integration and improves the automation level and production efficiency of port manufacturing by applying cutting-edge technologies for instance cloud computing and the Internet of Things[9]. Digital technology accelerate the exchange of digital logistics data and port ship data, reasonably arrange the order of ships entering and leaving the port, and shorten the residence time of goods. Based on the above analysis, Hypothesis 1 is proposed:

H1: Digital technology can directly impact the development of port logistics.

3.2 Digital Technology Has an Indirect Impact on the Development of Port Logistics

Digital technology can effectively improve traditional production and industrial organization models, driving the upgrading of industrial structures. It can promote the digitization of industries, and accelerating the transition of industrial structures towards the secondary and tertiary sectors[10]. The port logistics industry belongs to the tertiary industry, and the continuous upgrading of its industrial structure will promote the sustainable development of ports and enhance port logistics efficiency.

Digital technology facilitates the comprehensive digital transformation of traditional industries, with vast data resources attracting foreign investments and collaborations. It optimizes the foreign investment environment and helps Chinese ports align with international ports[11], strengthening import and export trade exchanges. Based on the above analysis, Hypothesis 2 is proposed:

H2: Digital technology influences port logistics by promoting industrial structure upgrading and attracting foreign investment.

3.3 Digital Technology Has a Threshold Effect on the Development of Port Logistics

Currently, the leading and supporting role of digital technology in the process of port logistics development in China is becoming increasingly prominent. However, due to differences in infrastructure and industrial structures across regions, the role of digital technology in port logistics may exhibit certain nonlinear characteristics. At a lower level of digital technology, various resources are relatively scarce[12], lack of intelligent network infrastructure, which will curb digital technology positive impact of port logistics. At a higher level of digital technology, it facilitates a positive interaction between digital technology and the allocation of production factors, effectively leveraging collaborative innovation and resource allocation effects. This makes the enabling effect of digital technology on the development of port logistics even more significant. Based on this, Hypothesis 3 is proposed:

H3: There is a nonlinear relationship in the influence of digital technology on the development of port logistics.

4 RESEARCH DESIGN

4.1 Model Construction

Baseline Regression Model. This study employs a dual fixed-effects model of regions and years to empirically test the impact of digital technology on the development of port logistics. The baseline regression model is as follows:

$$PL_{it} = \alpha_0 + \alpha_1 DT_{it} + \alpha_2 Control_{it} + \tau_i + \mu_t + \varepsilon_{it} \quad (1)$$

In which i and t represent different cities and years respectively. PL to be explained variable, on behalf of the port logistics development level. DT is the core explanatory variable, which represents the development level of digital technology. Control represents the control variables. τ and μ denote individual and time effects, respectively, while ε represents the random disturbance term. α_0, α_1, and α_2 are the estimated parameters.

Mediating Effect Model. this study borrows the "two-step approach" from Jiang Ting[13]to construct the following mediation effect test model:

$$ISU_{it} = \alpha_0 + \alpha_1 DT_{it} + \alpha_2 Control_{it} + \tau_i + \mu_t + \varepsilon_{it} \quad (2)$$

$$FDI_{it} = \alpha_0 + \alpha_1 DT_{it} + \alpha_2 Control_{it} + \tau_i + \mu_t + \varepsilon_{it} \quad (3)$$

In the figure, ISU_{it} and FDI_{it} are the intermediate variables of industrial structure upgrading and foreign investment, respectively. Other symbols have the same meaning as above.

Threshold Regression Model. Considering the digital technology and the possible existence of nonlinear relationship between port logistics development, this research adopts the threshold regression model test digital technology development of port logistics development of nonlinear effects. The basic form of the model is set as follows:

$$PL_{it} = \alpha_0 + \alpha_1 DT_{it} I(Z \le \gamma_1) + \alpha_2 DT_{it} I(Z > \gamma_1) + \alpha_3 Control_{it} + \tau_i + \mu_t + \varepsilon_{it} \quad (4)$$

DT is the core explanatory variable and also the threshold variable. γ_1 is the threshold to be estimated, I(·)is the representative function. If the conditions are met, I(·)=1, otherwise, I(·)=0. The meanings of other symbols are the same as above.

4.2 Variable Selection and Data Sources

Explained Variable. The explained variable of this study is the development level of port logistics. Based on data availability, an indicator system is established from two dimensions: port infrastructure and port carrying capacity. The entropy method is used to measure the logistics development level of major ports in the southwestern coastal areas and port clusters in China, denoted as PL.

Core Explanatory Variables. The explained variable in this study is the development level of digital technology. An indicator system is constructed by digital infrastructure, digital industry development, and digital technology innovation and eight subdivided indicators. The details are shown in Table 1. The digital technology development level of the cities where the main ports of China's southwest coastal port group are located is measured by the entropy method, expressed as DT.

Table 1. Digital Technology and Port Logistics Index System

First-Level Indicators	Second-Level Indicators	Third-Level Indicators	sign
Digital technology development level	Digital infrastructure	Number of Internet broadband access users	+
		Number of mobile phone households	+
		Number of landline telephone households	+
	Digital industry development	Telecommunication traffic	+
		Postal traffic	+
		Number of employees in information technology services	+
	Digital technology innovation	R&D investment	+
		Number of R&D personnel	+
Port logistics development level	Port infrastructure	Wharf length	+
		Number of pier berths	+
	Port carrying capacity	Cargo throughput	+
		Container throughput	+

Mediating Variables. The mediating variables chosen in this study are industrial structure upgrading and foreign investment. For industrial structure upgrading (ISU), using the weighted average of the ratio of value added of primary, secondary and tertiary industries to regional GDP. Foreign investment (FDI) is represented by the ratio of actual foreign capital utilized in the current year to the regional GDP.

Control Variables. to more precisely analyze the influence of digital technology on the development of port logistics in the southwestern coastal areas of China, the following control variables are set: fixed asset investment level (FI), measured as the ratio of gross fixed asset investment to GDP, urbanization level (UR), represented by the ratio of the total urban population at the end of the year to the regional total population; human capital (HC), indicated by the ratio of regional education expenditure to GDP. and the degree of industrial development (ID), expressed as the ratio of regional industrial added value to GDP.

Threshold Variables. Drawing on Hansen's research[14], this study selects the core explanatory variables that the development level of digital technology (DT) as threshold variables to test their specific threshold effects in influencing the development of port logistics.

4.3 Data Sources and Descriptive Statistics

This study focuses on six major ports in the southwestern coastal port cluster of China: Haikou Port, Yangpu Port, Beihai Port, Fangchenggang Port, Qinzhou Port, and Zhanjiang Port, as well as the relevant data of the cities where these ports are located. The research sample interval is set from 2005 to 2022. The data principally came from *China Statistical Yearbook, China Ports Yearbook,* EPS global database and the bulletin of each city. For some missing data, linear interpolation method was used to complete the data. The descriptive statistics of the variables are shown in Table 2.

Table 2. Descriptive statistics

VarName	Obs	Mean	SD	Min	Median	Max
PL	108	0.244	0.172	0.002	0.208	0.746
DT	108	0.200	0.151	0.028	0.146	0.552
IF	108	0.699	0.302	0.055	0.692	1.393
UR	108	0.230	0.176	0.054	0.184	0.676
HC	108	0.036	0.047	0.001	0.014	0.195
ID	108	0.283	0.146	0.028	0.331	0.507

5 EMPIRICAL RESULTS

5.1 Baseline Regression Analysis

In this research, the fixed-effects model is employed for regression analysis to examine the relationship between digital technology and port logistics development. The baseline regression results are presented in Table 3.

Table 3. Benchmark regression

	(1)	(2)
VARIABLES	PL	PL
DT	0.474**	0.513**
	(0.192)	(0.216)
IF		0.102**
		(0.040)
UR		0.241
		(0.162)
HC		0.221
		(0.211)
ID		-0.255
		(0.179)
Constant	-0.025	-0.061
	(0.045)	(0.104)
Observations	108	108
R-squared	0.790	0.827
yearfix	YES	YES
idfix	YES	YES

Column (1) displays the regression results without including control variables. It is observed that the regression coefficient of DT is significantly positive at the 5% level, with a value of 0.474. Even after incorporating control variables, the regression result remains significantly positive. This strongly validates the significant role of digital technology in promoting port logistics development, thus verifying Hypothesis 1 of this study.

5.2 Mechanism Analysis

Existing research has shown that the upgrading of industrial structure and foreign investment can facilitate the enhancement of port logistics. Wang[15] believes the upgrading of industrial structure is beneficial to accelerating the development of port logistics industry. Ye[16]proves through research that attracting foreign investment can effectively promote the development of port logistics. To examine the mediating role of digital technologies in development of port logistics, we conducted regression analysis on models (2) and (3) using industrial structure upgrading(ISU) and foreign investment (FDI) as mediating variables.

Table 4. Mediating effects test

	(1)	(2)
VARIABLES	ISU	FDI
DT	0.230**	0.190**
	(2.640)	(3.479)
IF	0.015	0.001
	(0.373)	(0.048)
UR	-0.200**	-0.198*
	(-2.829)	(-2.460)
HC	1.135***	0.062
	(10.619)	(0.599)
ID	0.007	0.014
	(0.083)	(0.145)
Constant	0.069***	0.068*
	(5.839)	(2.103)
Observations	108	108
R-squared	0.601	0.316
yearfix	YES	YES
idfix	YES	YES

In Table 4, column (1) shows that the regression coefficient of digital technology development (DT) on industrial structure upgrading (ISU) is positive and significant at the 5% level, indicating that digital technology can enhance the development of port logistics by promoting industrial structure upgrading. In column (2), the effect of digital technology development on foreign investment (FDI) is also significantly positive at the 5% level, suggesting that digital technology contributes to port logistics development by attracting foreign investment, thus verifying Hypothesis 2 of this study.

5.3 Robustness and Endogeneity Tests

Exclusion of Partial Samples. Due to the impact of the COVID-19 pandemic on China's capital market from 2019 to 2021, which may have caused undetected effects on the causal identification of this study, we excluded the samples from 2019 to 2021 and retained only the remaining 15-year samples. Observing column (1) of Table 5, the regression results remain robust.

Table 5. Stability test

	(1)	(2)
	Exclusion of Partial Samples	Addition of Control Variables
VARIABLES	PL1	PL
DT1	0.494**	
	(0.210)	
DT		0.536**
		(0.220)
IF	0.049	0.104**
	(0.039)	(0.040)
UR	0.223	0.244
	(0.158)	(0.162)
HC	0.299	0.264
	(0.216)	(0.221)
ID	-0.163	-0.287
	(0.167)	(0.186)
ED		0.022
		(0.033)
Constant	-0.060	-0.069
	(0.099)	(0.105)
Observations	90	108
R-squared	0.829	0.828
yearfix	YES	YES
idfix	YES	YES

Addition of Control Variables. To eliminate potential interference from omitted variables on the baseline regression results, we conducted a robustness test by adding the macro-level control variable of regional economic development level (ED) to the baseline regression model. The regional economic development level was measured using the logarithm of per capital GDP. As can be seen from the regression results in Column (2) of Table 5, after adding control variables, there is no obvious difference with previous, verifying the robustness of the benchmark regression results.

In summary, whether removing part of the samples or adding control variables, the regression results are not significantly different from the benchmark regression results, which further proves the robustness of the benchmark regression results.

5.4 Endogeneity test

To alleviate the endogenous problems caused by the possible causal relationship between digital technology and port logistics development. Using the one-period lag in digital technology development as an instrumental variable, we conducted a two-stage least squares estimate, and the results as shown in Table 6.

Table 6. Endogeneity test

	(1)	(2)
	First	Second
VARIABLES	PL	PL
L.DT	0.334*	
	(0.184)	
DT		0.961***
		(0.233)
Contral	YES	YES
Constant	0.495	-0.335
	(0.194)	(0.259)
Observations	102	102
R-squared	0.975	0.901
yearfix	YES	YES
idfix	YES	YES

Column (1) in Table 6 is the regression the first phase of the results, indicating that digital technology has been a significant enabler on port logistics development, and the relationship between the two is relatively stable. The results of Column (2) show that there is a significant positive correlation between digital technology and the development level of port logistics. In summary, the conclusion that digital technology can facilitate the development of port logistics is robust and reliable.

5.5 Threshold Effect Analysis

Using the core explanatory variable, digital technology development level(DT), as the threshold variable. First, a threshold effect test is conducted on the two threshold variables. The results of 300 test thresholds sampled through Bootstrap are shown in Table 7.

Table 7. Threshold effect test

Threshold Variables	mode	Fstat	Prob	Critical values for different levels of significance		
				10%	5%	1%
DT	Single threshold	44.23	0.044	35.7919	43.3082	60.0221
	Second threshold	18.11	0.386	30.3516	37.4043	53.2703

The results showed that only a single threshold effect between digital technology and port logistics, which is significant at the 5% level. According to the threshold value LR image in Figure 1, the threshold value intersects with the horizontal line. The significance test is passed, thus verifying that the threshold value obtained using the single threshold model in this paper is authentic and effective.

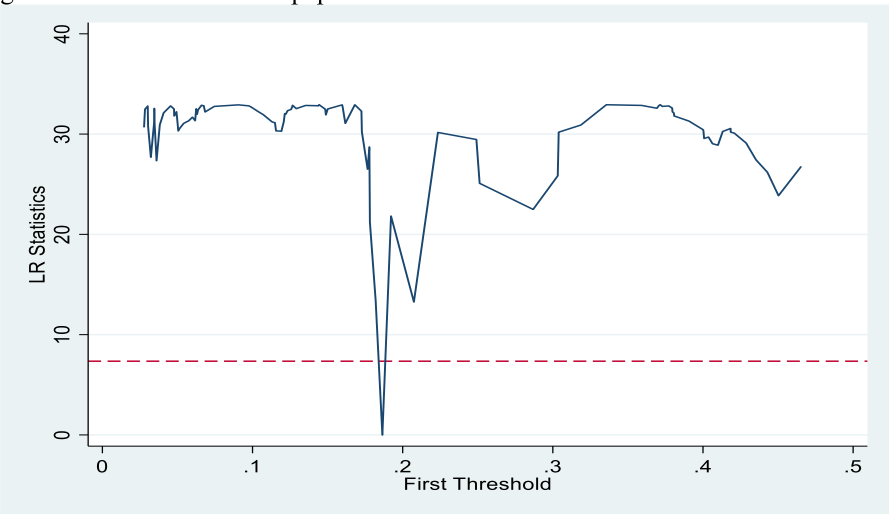

Fig. **1.** Threshold value LR image

Setting up a regression model with a single threshold and the regression results are presented in Table 8. As can be seen from the table, when the digital technology development level is below the threshold, it has a negative impact on port logistics, but this impact is not significant. This may that in the early stages of digital technology infrastructure and investment in research and development was relatively low. However, once the level of digital technology development surpasses the first threshold value, the impact coefficient rises from 0.135 to 1.005, and the effect on port logistics becomes significant. The results indicate that as the level of digital technology development increases, the role of digital technology in promoting port logistics development exhibits a nonlinear characteristic of positive marginal increment, with a clear threshold effect. This verifies Hypothesis 3 of this paper.

Table 8. Threshold regression results

VARIABLES	(1) PL
DT(DT≤0.1865)	-0.235
	(0.460)
DT(DT＞0.1865)	0.615**
	(0.254)
Constant	-0.100
	(0.141)
Contral	YES
Observations	108
yearfix	YES
idfix	YES

6 CONCLUSIONS AND RECOMMENDATIONS

This paper selects panel data from six major ports in China's southwestern coastal port cluster from 2005 to 2022, measures the level of digital technology development and port logistics development using the entropy method, and empirically analyzes the role and mechanism of digital technology on port logistics using a dual fixed-effects model. The main conclusions drawn are as follows:

Digital technology significantly drives the development of port logistics. This conclusion remains stable after changing the measurement method of the core explanatory variable, excluding some samples, adding control variables, and addressing endogeneity issues.

Digital technology has also promoted the development of port logistics by driving industrial structure upgrading and attracting foreign investment.

Digital technology has a nonlinear effect on the development of port logistics. When the digital technology development level is used as a threshold variable, the influence of digital technology on port logistics shows a single threshold effect, and the promoting effect of digital technology significantly increases when crossing the threshold.

The study findings of this paper provide the following suggestions for optimizing the development path of digital technology enabling port logistics in China:

Strengthen research and development innovation in digital technology and deepen digital technology applied in port logistics industry adequately.

Coordinate and facilitate industrial structure upgrading and attract foreign investment in the port logistics industry.

Increase investment in digital technology in the port logistics industry and address issues in the construction of digitalized ports.

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