



# Research on Digital Transformation Pathways of Port Enterprises: An Analysis Based on fsQCA and NCA Methods

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**Abstract.** This study takes 13 listed port enterprises in China as the research sample. Based on the TOE framework, six driving factors are constructed, namely digital R&D investment, technological application capability, strategic flexibility, investment allocation capability, policy support intensity, and industry competitive pressure. The fsQCA and NCA methods are employed to identify the key conditions and configuration paths for port enterprises to achieve a high level of digital transformation. The results indicate that digital transformation in port enterprises is the outcome of the synergistic effects of multiple conditions. Policy support and technological investment serve as critical constraining conditions in the transformation process, and different ports can achieve high-level digital transformation through differentiated configuration paths. This study provides empirical evidence for port enterprises in formulating digital transformation strategies and for relevant authorities in policy-making.

**Keywords:** Port Enterprises; Digital Transformation; fsQCA; NCA.

## 1 Introduction

With the expansion of global trade, ports have become key hubs in global supply chains. In recent years, the port industry has developed rapidly, characterized by rising throughput and the expansion of container transport and multimodal logistics<sup>[1]</sup>. Meanwhile, intelligentization, automation, and green low-carbon development have become major directions of port transformation<sup>[2]</sup>. Increasing global competition has highlighted differences in technological application, organizational management, and resource allocation, leading to heterogeneous digital transformation outcomes.

Port digital transformation is not only a technological upgrade but also a process involving technological investment, organizational adjustment, and environmental adaptation. Differences in resources and institutional environments lead ports to pursue transformation through distinct factor combinations, reflecting strong multi-factor interactions. However, most existing studies rely on linear approaches that struggle to capture such configurational mechanisms, and limitations remain in indicator measurement and evaluation standards<sup>[3-5]</sup>.

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To address these gaps, this study examines 13 Chinese listed port enterprises. Based on the Technology–Organization–Environment (TOE) framework, six conditions are identified: digital R&D investment, technological application capability, strategic flexibility, investment allocation capability, policy support intensity, and industry competitive pressure. By integrating Necessary Condition Analysis (NCA) and Fuzzy-Set Qualitative Comparative Analysis (fsQCA), this study identifies key drivers and configurational pathways of port digital transformation, providing evidence for differentiated transformation strategies and policy design.

## 2 Research Design

### 2.1 Research Framework and Method

The Technology-Organization-Environment (TOE) framework is widely used to analyze firm transformation, emphasizing the joint influence of internal conditions and external environments on organizational change. Based on this framework, this study develops an analytical model of “driving factors-configurational paths-transformation outcomes”, viewing port digital transformation as a process shaped by the interaction of technological, organizational, and environmental conditions rather than by a single factor.

To examine these interactions, this study integrates Fuzzy-Set Qualitative Comparative Analysis (fsQCA) and Necessary Condition Analysis (NCA). FsQCA is suitable for analyzing complex causal relationships and identifying multiple equivalent configurations leading to the same outcome, overcoming the limitations of traditional linear approaches [6]. NCA is further used to test whether specific factors constitute necessary conditions and to identify bottleneck constraints in achieving high-level digital transformation. The combined application of fsQCA and NCA thus reveals multiple transformation pathways while clarifying the roles of different driving factors.

### 2.2 Sample Selection and Data Sources

This study selects 13 representative Chinese port enterprises as the research sample. As shown in Table 1, these ports are distributed across major port clusters in North, East, South, and Southwest China and differ in scale, location, business structure, and development stage, providing a representative overview of China’s port industry.

**Table 1.** Characteristics of Sample Port Enterprises.

Port Enterprise	Region	Primary Functional Positioning
Qinhuangdao Port	North China	Energy transportation hub
Tangshan Port	North China	Regional hub port
Tianjin Port	North China	International hub port
Qingdao Port	East China	International hub port
Rizhao Port	East China	Energy and raw material port
Lianyungang Port	East China	New Eurasian Land Bridge node

Nanjing Port	East China	Yangtze River trunk-line hub
Shanghai Port	East China	Global hub port
Ningbo-Zhoushan Port	East China	International hub port
Xiamen Port	South China	Regional hub port
Guangzhou Port	South China	Regional hub port
Zhuhai Port	South China	Regional port
Beibu Gulf Port	Southwest China	Western Land–Sea New Corridor hub

Regarding data sources, this study uses a sample period from 2022 to 2024. Data are mainly collected from publicly disclosed annual and ESG reports of port enterprises. Additional industry-level data, such as port throughput and market share, are obtained from statistical materials published by the National Bureau of Statistics, the Ministry of Transport, and port industry associations.

### 2.3 Variable Definition and Measurement

1. Outcome Variable: Level of Digital Transformation. This study uses the Smart Port Index jointly released by Debon Consulting and the eNet Internet Research Institute to measure the level of digital transformation. The index evaluates port performance across multiple dimensions, including digitalization, intelligentization, and green development, and provides standardized data for analyzing digital transformation pathways.

2. Technological Factors. Following Fu Jincun et al. [7], two indicators are selected: digital R&D investment and technological application capability. Digital R&D investment is measured by the ratio of technological R&D expenditure to operating revenue, reflecting firms' investment intensity in digital technologies. Technological application capability reflects employees' ability to adopt digital technologies and is measured by the proportion of employees with a bachelor's degree or above.

3. Organizational Factors. Organizational factors include strategic flexibility and investment allocation capability. Following Zhang Wukang et al. [8], strategic flexibility is measured by the ratio of total liabilities to total assets, reflecting firms' capacity for strategic adjustment. Investment allocation capability is measured by the ratio of long-term equity investment to total assets, indicating the ability to coordinate external resources.

4. Environmental Factors. Environmental factors include policy support intensity and industry competitive pressure. Policy support intensity is measured following Kang Zhiyong et al. [9] by the annual total government subsidies received by the enterprise, with a logarithmic transformation applied to reduce extreme-value effects. Industry competitive pressure is measured by the proportion of a port's annual throughput relative to total market throughput, reflecting market competition intensity.

### 2.4 Data Calibration

Calibration converts raw data into fuzzy-set membership scores and is a key step in fsQCA [11]. This study adopts the direct calibration method, using the 90th, 50th, and 10th percentiles as the thresholds for full membership [12], the crossover point, and full

non-membership, respectively. This approach is widely used when theoretical thresholds are unavailable because it reflects the empirical distribution while reducing the influence of extreme values. All continuous variables are calibrated into fuzzy-set scores within the  $[0,1]$  interval, and the calibration anchors are reported in Table 2.

**Table 2.** Calibration Anchors of Variables.

Antecedent Conditions		Anchor point		
		10%	50%	90%
Technological Dimension	DRDI	0.1037	0.0479	0.0089
	TAC	0.5705	0.3404	0.1993
Organizational Dimension	SF	0.5599	0.3098	0.1155
	IAC	0.0192	0.0023	0.0000
Environmental Dimension	PSI	19.5180	17.5913	15.2496
	ICP	0.0670	0.0336	0.0087
Outcome	DT	95.1910	92.9300	84.6280

### 3 Research Results

#### 3.1 Necessary Condition Analysis

The NCA method tests whether antecedent conditions are necessary for the outcome and quantifies their constraining effects through bottleneck tables. In this study, effect sizes ( $d$ ) for 6 antecedent conditions are calculated using Ceiling Regression (CR) and Ceiling Envelopment (CE). According to NCA criteria, a condition is considered necessary only if the effect size  $d \geq 0.1$  and passes the Monte Carlo permutation test ( $P < 0.01$ )<sup>[10]</sup>. Table 3 reports the results. Although some conditions approach the threshold, none meet both requirements. Thus, no antecedent condition is an independent necessary condition for port digital transformation.

**Table 3.** Results of NCA Necessary Condition Analysis.

Conditions	Method	Accuracy	Ceiling Zone	Effect Size ( $d$ )	P-value
DRDI	CR	92.30%	0.019	0.022	0.764
	CE	100.00%	0.025	0.029	0.770
TAC	CR	100.00%	0.075	0.088	0.637
	CE	100.00%	0.150	0.176	0.546
SF	CR	76.90%	0.200	0.231	0.139
	CE	100.00%	0.135	0.157	0.320
IAC	CR	92.30%	0.138	0.163	0.220
	CE	100.00%	0.197	0.232	0.081
PSI	CR	84.60%	0.222	0.260	0.041
	CE	100.00%	0.271	0.317	0.021
ICP	CR	76.90%	0.311	0.359	0.036

Bottleneck levels reflect the minimum thresholds that each antecedent condition must reach at different stages of digital transformation Table 4 reports the results. To achieve 100% digital transformation, the bottleneck levels are 20.5% for digital R&D investment, 62.9% for technological application capability, 52.4% for strategic flexibility, 70.8% for investment allocation capability, and 66.2% for industry competitive pressure. The bottleneck effect of policy support intensity is not clearly observed.

**Table 4.** Bottleneck Level Analysis Results (%).

DT Level	DRDI	TAC	SF	IAC	PSI	ICP
0	NN	NN	NN	NN	NN	NN
10	NN	NN	NN	NN	NN	NN
20	NN	NN	NN	NN	NN	NN
30	NN	NN	NN	8.8	NN	3.0
40	NN	NN	NN	17.6	NN	12.0
50	NN	NN	NN	26.5	NN	21.1
60	NN	NN	7.2	35.4	NN	30.1
70	NN	2.7	18.5	44.2	NN	39.1
80	NN	22.8	29.8	53.1	NN	48.1
90	4.4	42.8	41.1	62.0	NN	57.2

To further validate the NCA results, fsQCA was used to test the necessity of antecedent conditions. A condition is considered necessary if its consistency with the outcome reaches 0.9<sup>[14]</sup>. Calibrated data were analyzed in fsQCA 3.0, with results shown in Table 5. All consistency values were below 0.9, indicating that no single condition is necessary for digital transformation. This aligns with the NCA findings, confirming the multi-factor synergistic nature of the process.

**Table 5.** Tests of Single Antecedent Conditions.

Antecedent Conditions	Outcome variables			
	High-Level DT		Non-High-Level DT	
	Consistency	Coverage	Consistency	Coverage
DRDI	0.553949	0.661293	0.612101	0.565055
TAC	0.622016	0.698422	0.608397	0.528259
SF	0.658982	0.706183	0.550362	0.456074
IAC	0.518483	0.677419	0.576821	0.582784
PSI	0.724458	0.790210	0.497442	0.419580
ICP	0.670986	0.864651	0.472746	0.471084
~DRDI	0.635657	0.679399	0.633092	0.523254
~TAC	0.579866	0.656931	0.652672	0.571782
~SF	0.492429	0.586134	0.645440	0.594090
~IAC	0.680671	0.675328	0.680720	0.522263
~PSI	0.467876	0.546265	0.751279	0.678293
~ICP	0.589551	0.591164	0.864174	0.670086

### 3.2 Configurational Analysis

FsQCA 3.0 was applied to analyze configurations leading to high and non-high digital transformation in port enterprises. The case frequency threshold was set to 1 (covering over 75% of cases) and the consistency threshold to 0.8 [13]. Truth tables were recoded to obtain complex, intermediate, and parsimonious solutions; conditions appearing in both intermediate and parsimonious solutions were treated as core, and those only in the intermediate solution as peripheral. Table 6 identifies four configurations leading to high-level digital transformation. The overall solution consistency is 0.9228 and coverage 0.6358, indicating strong explanatory power.

**Table 6.** Configurational Paths for Digital Transformation Levels.

Antecedent Conditions	High-Level DT				Non-High-Level DT	
	H1	H2	H3	H4	NH1a	NH1b
DRDI	⊗	⊗		●	●	⊗
TAC	⊗	●	⊗	●	⊗	⊗
SF	●	●	⊗	●	⊗	⊗
IAC	⊗	●	●	⊗	●	⊗
PSI	●	⊗	●	●	⊗	⊗
ICP	⊗	●	●	●	⊗	⊗
Raw Coverage	0.2198	0.3287	0.2414	0.2769	0.2736	0.2930
Unique Coverage	0.0915	0.1350	0.1200	0.0832	0.0672	0.0866
Consistency	0.9938	0.8860	0.9516	0.9951	0.8960	0.9072
Overall Consistency		0.6358			0.3602	
Digital R&D Investment		0.9228			0.9190	

Note: ●= peripheral condition present; ●= core condition present; ⊗= peripheral absent; ⊗= core absent; blank= condition irrelevant (either present or absent).

**Configurational Paths toward High-Level Digital Transformation. Path H1:** Policy-Strategy Compensation Type. This path features low digital R&D investment, high strategic flexibility, and low investment allocation as core conditions, with weak technological application, strong policy support, and low competitive pressure as peripheral conditions. Firms with strong strategic flexibility can leverage policy resources and internal reallocation to achieve digital transformation despite limited R&D, though reliance on external collaboration increases if technological capability is low. Sustainability may decline if policy support weakens. Xia-men Port exemplifies this path, using cross-strait shipping advantages, free trade policies, flexible organization, and local government facilitation to respond rapidly to emerging business demands despite limited R&D.

**Path H2:** Flexibility-Market Adaptation Type. In this configuration, high investment allocation and strong industry competition are core, while low R&D, high strategic flexibility, strong technological application, and weak policy support are peripheral. Intense competition and available capital drive adaptation, and internal flexibility converts pressure into efficiency gains. With limited R&D, firms rely on organizational

and talent mechanisms to operationalize external technologies. Lianyungang Port exemplifies this path, using automated terminals and strong technological capability to enhance efficiency under fierce regional competition, despite limited policy support.

**Path H3:** Externally Driven High-Pressure Type. This path features high investment allocation, strong policy support, and intense industry competition as core, with low strategic flexibility and weak technological application as peripheral. Transformation is driven by external capital, institutional support, and competition, requiring effective absorption of resources to avoid fragmented investments. Qingdao Port exemplifies this path, leveraging its open port economy, international logistics partnerships, and supportive provincial policies to advance digital transformation.

**Path H4:** Endogenous Demonstration Type. Strong policy support and intense competition are the core conditions, with high R&D investment, strategic flexibility, technological application, and low investment allocation as peripheral. Transformation relies on internally developed technologies and institutionalized mechanisms rather than large-scale external investment. Shanghai Port exemplifies this path, leveraging the Shanghai International Shipping Center, leading internal capabilities, and government support to deploy IoT monitoring systems and automated equipment, establishing a benchmark for digital transformation.

**Configurational Paths toward Non-High-Level Digital Transformation.** Path NH1a indicates that although firms possess some R&D and investment activity, insufficient strategic flexibility, weak technological application capability, and lack of policy support prevent these inputs from evolving into sustainable digital capabilities, resulting in fragmented and limited transformation outcomes. Path NH1b reflects a comprehensive disadvantage across internal and external conditions. Low strategic flexibility, weak technological application capability, and absence of policy support restrict adaptive capacity, causing digital transformation to stagnate at a persistently low level despite occasional project initiatives.

### 3.3 Robustness Test

This study conducts robustness testing by increasing the original consistency threshold, following prior research<sup>[14]</sup>. Specifically, the consistency threshold is raised from 0.80 to 0.85, while all other parameters and analytical procedures remain unchanged. The recalibration and analysis are performed using fsQCA 3.0. The results indicate that, after increasing the consistency threshold, the configurational outcomes for both high-level and non-high-level digital transformation remain consistent with those obtained under the original threshold. The core and peripheral conditions of each configuration do not change, and only minor fluctuations are observed in overall solution consistency and coverage. These findings suggest that the research conclusions are not sensitive to variations in the consistency threshold, demonstrating strong robustness and reliability.

## 4 Conclusions and Future Research

This study investigates digital transformation in Chinese port enterprises using the TOE framework, fsQCA, and NCA. Results show that high-level transformation arises from the joint effects of multiple conditions rather than any single factor, with several equifinal paths identified, including policy-strategy compensation, flexibility-market adaptation, and external pressure-driven configurations. Configurations for non-high transformation highlight key hindering combinations.

These findings provide practical guidance: technologically advanced firms should leverage internal strengths and market opportunities, while less advanced firms need to enhance strategic flexibility, attract digital talent, and strengthen external collaboration. Policymakers should design differentiated support policies considering firm heterogeneity.

Limitations include the small sample of 13 Chinese listed ports, which may limit generalizability despite covering major regions and hubs. Future research could expand the sample to non-listed ports, ports in other countries, or multi-year data to test robustness. Additionally, fsQCA and NCA lack temporal dynamics; future studies could integrate methods such as structural equation modeling or system dynamics to capture the evolution of digital transformation.

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## Definitions/Abbreviations

DRDI	Digital R&D Investment	IAC	Investment Allocation Capability
TAC	Technological Application Capability	PSI	Policy Support Intensity
SF	Strategic Flexibility	ICP	Industry Competitive Pressure
DT	Digital Transformation		

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