

# *Artificial Intelligence-driven on Digital Transformation: A Strategic Framework for International Port Operation Competitiveness*

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**Keywords:** Artificial Intelligence, International Port Operation Competitiveness, Digital Transformation Strategy

**Abstract:** This study aims to analyze the key factors influencing the success of BBW Port Group's AI-driven digital transformation and to develop a strategic framework for its implementation. The study employs a quantitative research methodology, utilizing data collected from 212 personnel at BBW Port Group who are engaged in digital transformation and AI technology applications. The research instrument underwent rigorous testing for Item-Objective Congruence (IOC), validity, and reliability. Data analysis was conducted using descriptive statistics, correlation analysis, and regression analysis. The results indicate that AI system integration capabilities, data quality and validity, technology adoption and innovation, AI-driven automation levels, AI system scalability and flexibility, change management and senior management support, and market and policy pressures all have a significant positive impact on international port operational competitiveness. This research enriches the theoretical framework regarding AI applications in port operations and holds significant theoretical and practical value for promoting the comprehensive upgrading and development of China's port industry.

## 1. Introduction

Amid profound shifts in global trade patterns and technological innovation, the international port industry faces increasingly complex operational challenges. These include imperatives for enhanced logistics efficiency, cost optimization, and continuous improvement in customer service. Concurrently, accelerated global economic integration and deepening regional cooperation have elevated ports to pivotal roles as core nodes within global supply chains. International ports have evolved from traditional cargo transfer points into complex systems integrating logistics, supply chain collaboration, and comprehensive services. Consequently, the rapid advancement of artificial intelligence (AI) has positioned digital transformation as a core strategy for port enterprises aiming to enhance efficiency, optimize resource allocation, and address complex supply chain challenges.

As a central hub for China-ASEAN cooperation, the BBW Port Group serves as China's southern gateway to the Maritime Silk Road, maintaining direct connections with ASEAN economies. By

supporting the development of coastal industrial clusters through modern operations, the port facilitates regional economic integration. However, compared to leading international hubs such as the Port of Singapore and Busan Port, BBW Port lags in equipment automation, information technology adoption, and overall operational efficiency [1].

Therefore, this study pursues two primary objectives. First, it aims to analyze the critical determinants influencing the success of BBW Port Group's AI-driven digital transformation. Second, it seeks to develop a strategic framework for this transformation to serve as a guideline for enhancing the port's international operational competitiveness. Although this research focuses on BBW Port Group as a case study, the challenges addressed reflect broader issues within the global port industry, thereby offering wider theoretical and practical implications.

## 2. Literature Review

The Technology-Organization-Environment (TOE) framework is a comprehensive theoretical model primarily used to analyze the organizational adoption and implementation of innovations, particularly in the field of information technology. Multiple studies indicate that the TOE framework comprises three core elements—technological characteristics, organizational attributes, and environmental factors—which collectively influence organizational decision-making processes [2]. Initially proposed by Tornatzky and Fleischer [3], this model has since been widely applied to understand the willingness and behavior associated with adopting various technological solutions. The framework's applicability extends beyond IT adoption, serving as an effective tool for analyzing organizational responses to new theories and innovations.

In the context of port operational competitiveness, recent research has examined the impact of digital transformation, particularly the integration of AI-driven technologies. For instance, Popa et al optimized multimodal livestock transport operations at Romanian Black Sea ports by applying business process modeling and simulation-based optimization [4]. Their study demonstrated the synergistic role of technological and organizational factors in boosting operational efficiency. Similarly, Al-Ajmi et al employed an extended TOE framework to analyze the digital transformation of Oman's shipping industry [5], highlighting the critical role of advanced technologies such as IoT, blockchain, AI, and automation. Furthermore, practices within Chinese port enterprises demonstrate that technological tools like IoT and AI can be leveraged to optimize business processes and resource management, thereby enhancing competitiveness [6]. In summary, the reviewed literature collectively confirms that the TOE framework provides a comprehensive lens for understanding the multifaceted factors influencing AI-driven digital transformation in ports.

## 3. Research Hypothesis

### 3.1 Technological Factors

Drawing on the Resource-Based View (RBV), this capability eliminates information silos and optimizes decision-making by seamlessly connecting internal and external infrastructures [7]. It transforms ports into predictive platforms, significantly enhancing operational efficiency [8][9].

H1: AI System Integration Capability has a positive and significant relationship with International Port Operation Competitiveness.

As the foundational infrastructure for AI, high data quality (accuracy, completeness, consistency) is a prerequisite for effective decision-making [10]. Robust collection and standardization capabilities ensure organizations can effectively leverage AI tools during digital transformation [11][12].

H2: Data Quality and Readiness has a positive and significant relationship with International

Port Operation Competitiveness.

Grounded in the Technology Acceptance Model (TAM) and Diffusion of Innovations (DOI), the proactive adoption of AI directly enhances automation and service quality [13][14]. In the context of Industry 5.0, AI further acts as a catalyst for sustainable performance and green innovation [15][16].

H3: Technology Adoption and Innovation has a positive and significant relationship with International Port Operation Competitiveness.

Beyond simple task execution, AI-driven automation augments human labor through intelligent control and resource allocation [17]. High-level automation in critical operations (e.g., vessel scheduling) reduces costs and accelerates process efficiency.

H4: AI-driven Automation Level has a positive and significant relationship with International Port Operation Competitiveness.

Complex Adaptive Systems theory suggests that dynamic environments require adaptable architectures [18]. Scalability allows ports to respond rapidly to fluctuating throughput and technological shifts, ensuring long-term stability [19].

H5: AI System Scalability and Flexibility has a positive and significant relationship with International Port Operation Competitiveness.

### **3.2 Organizational Factors**

Successful transformation requires leadership intervention and resource allocation. Strong senior support fosters a culture conducive to technology adoption, whereas insufficient AI literacy acts as a barrier [20]. Strategies such as appointing a Chief Digital Officer and implementing agile methodologies are essential for AI organizational socialization [21].

H6: Change Management and Top Management Support has a positive and significant relationship with International Port Operation Competitiveness.

### **3.3 Environmental Factors**

Institutional theory posits that organizational behavior is driven by external legitimacy pressures. Intense market competition and government regulations compel ports to pursue digital transformation to ensure compliance, meet stakeholder expectations, and maintain competitiveness [22].

H7: Market and Policy Pressure has a positive and significant relationship with International Port Operation Competitiveness.

## **4. Research Design and Data Collection**

### **4.1 Scale Design**

Measurement items were adapted from established scales to fit the BBW Port Group context. Following a pilot test with 15 practitioners and expert reviews, the final 25-item instrument covers seven dimensions: AI system integration, data quality, technology adoption, automation level, scalability, management support, and market pressures. All items were measured on a 5-point Likert scale (1= 'Strongly Disagree' to 5= 'Strongly Agree')

### **4.2 Data Collection**

Data were collected via an online survey in September 2025, targeting digital transformation

personnel at BBW Port Group's three major ports (Qinzhou port, Fangcheng port, and Beihai port). Of the 250 distributed questionnaires, 212 valid responses were obtained, yielding an effective response rate of 84.8%. Respondent profiles included gender, education, tenure, department, position, and port familiarity.

## 5. Empirical Analysis

### 5.1 Reliability and Validity Tests

This study employed SPSS 17.0 to examine the reliability and validity of the measurement scale, thereby assessing the reliability and validity of the scale's measurement results. First, the reliability of the items was analyzed. The overall Cronbach's alpha values for each research variable exceeded 0.8, indicating that the scale data possessed good reliability.

Exploratory Factor Analysis (EFA) was conducted to assess the construct validity of the scale. The data demonstrated adequate sampling adequacy (KMO=0.812) and significant sphericity (Bartlett's test,  $p < 0.05$ ). Based on eigenvalues greater than 1, eight factors were extracted, aligning perfectly with the theoretical dimensions. Using Varimax rotation, the cumulative variance explained reached 78.526%. All item communalities exceeded 0.4, and each item exhibited strong loadings ( $\geq 0.762$ ) on its respective factor without significant cross-loadings. Consequently, the scale demonstrates sound construct validity, confirming consistency between the theoretical and observed structures.

### 5.2 Correlation Analysis

Table 1: Pearson correlation analysis matrix of independent variables and international port operation competitiveness.

	1	2	3	4	5	6	7	8
1.AI System Integration Capability	1	0.101	0.136*	0.349**	0.193**	0.210**	0.239**	0.328**
2.Data Quality and Readiness	0.101	1	0.142*	0.145*	0.105	0.171*	0.288**	0.313**
3.Technology Adoption and Innovation	0.136*	0.142*	1	0.195**	0.166*	0.201**	0.164*	0.312**
4.AI-Driven Automation Level	0.349**	0.145*	0.195**	1	0.077	0.249**	0.166*	0.341**
5.AI System Scalability and Flexibility	0.193**	0.105	0.166*	0.077	1	0.300**	0.147*	0.320**
6.Change Management and Top Management Support	0.210**	0.171*	0.201**	0.249**	0.300**	1	0.191**	0.383**
7.Market and Policy Pressure	0.239**	0.288**	0.164*	0.166*	0.147*	0.191**	1	0.326**
8.International Port Operation Competitiveness	0.328**	0.313**	0.312**	0.341**	0.320**	0.383**	0.326**	1

Note: N=212.

Variable definitions: 1=AI System Integration Capability; 2=Data Quality and Readiness; 3=Technology Adoption and Innovation; 4=AI-Driven Automation Level; 5=AI System Scalability and Flexibility; 6=Change Management and Top Management Support; 7=Market and Policy Pressure; 8 = International Port Operation Competitiveness.

\* $P < 0.05$ , \*\* $P < 0.01$ .

The results of the Pearson correlation analysis are presented in Table 1. As the table indicates, all seven independent variables demonstrated significant positive associations with International Port Operational Competitiveness. Notably, 'Change Management and Top Management Support' exhibited the strongest correlation ( $r=0.383, p<0.01$ ). Variables such as AI-driven automation level ( $r=0.341$ ), AI system integration capability ( $r=0.328$ ), and market pressures ( $r=0.326$ ) showed moderate correlations, suggesting that the depth of AI application constitutes a core source of technological competitiveness. Conversely, AI system scalability ( $r=0.320$ ), data quality ( $r=0.313$ ), and technology adoption ( $r=0.312$ ) displayed relatively weaker associations, characterizing them as

foundational elements for long-term adaptability.

Regarding the relationships among independent variables (Table 1), a notable correlation was observed between AI system integration capability and AI-driven automation levels ( $r=0.349$ ). Meanwhile, the relationship between AI system scalability and change management was statistically significant but relatively weaker ( $r=0.300$ ).

### 5.3 Regression Analysis

As presented in Table 2, the multiple linear regression model demonstrated significant explanatory power ( $F=16.747, p<0.001$ ), accounting for 34.3% of the total variance in international port operational competitiveness ( $\text{Adj. } R^2=0.343$ ). Diagnostic metrics, including a D-W value of 1.989 and low VIF scores, confirmed the absence of significant autocorrelation and multicollinearity. All seven independent variables exhibited significant positive effects ( $p<0.05$ ). Notably, 'Change Management and Top Management Support' yielded the highest standardized coefficient ( $\beta=0.181$ ), identifying it as the most critical driver. This was followed by technical factors such as Data Quality ( $\beta=0.168$ ), Scalability ( $\beta=0.166$ ), and Automation ( $\beta=0.161$ ), whereas AI System Integration ( $\beta=0.132$ ) and Market Pressures ( $\beta=0.135$ ) showed relatively weaker influences.

Table 2: Regression analysis results for international port operation competitiveness.

	B	Std.Error	Beta	t	p	VIF	Tolerance
Constant	-0.302	0.280	-	-1.078	0.282	-	-
AI System Integration Capability	0.125	0.058	0.132	2.146	0.033*	1.220	0.820
Data Quality and Readiness	0.171	0.060	0.168	2.836	0.005**	1.121	0.892
Technology Adoption and Innovation	0.151	0.058	0.153	2.613	0.010**	1.098	0.910
AI-Driven Automation Level	0.158	0.061	0.161	2.612	0.010**	1.215	0.823
AI System Scalability and Flexibility	0.164	0.059	0.166	2.777	0.006**	1.141	0.876
Change Management and Top Management Support	0.180	0.061	0.181	2.948	0.004**	1.210	0.826
Market and Policy Pressure	0.134	0.060	0.135	2.240	0.026*	1.175	0.851
Model Summary	R <sup>2</sup> =0.365, Adj R <sup>2</sup> =0.343, F (7,204)=16.747, p=0.000, D-W=1.989						

Note:\*P < 0.05 \*\*P < 0.01 \*\*\*P < 0.001

### 5.4 Hypothesis Testing

The regression results confirmed that all seven proposed hypotheses (H1-H7) are supported. Specifically, 'Change Management and Top Management Support' exerted the most substantial impact ( $\beta=0.181, p<0.01$ ), validating H6. Strong positive effects were also observed for Data quality and readiness (H2), AI system scalability and flexibility (H5), AI-driven automation level (H4), and technology adoption and innovation (H3), with standardized coefficients ranging from 0.153 to 0.168. Although 'AI System Integration capability' (H1) and 'Market and policy pressures' (H7) demonstrated comparatively weaker effect sizes, their positive influences remained statistically significant ( $p<0.05$ ). Based on these validated relationships, the strategic framework is illustrated in Figure 1.

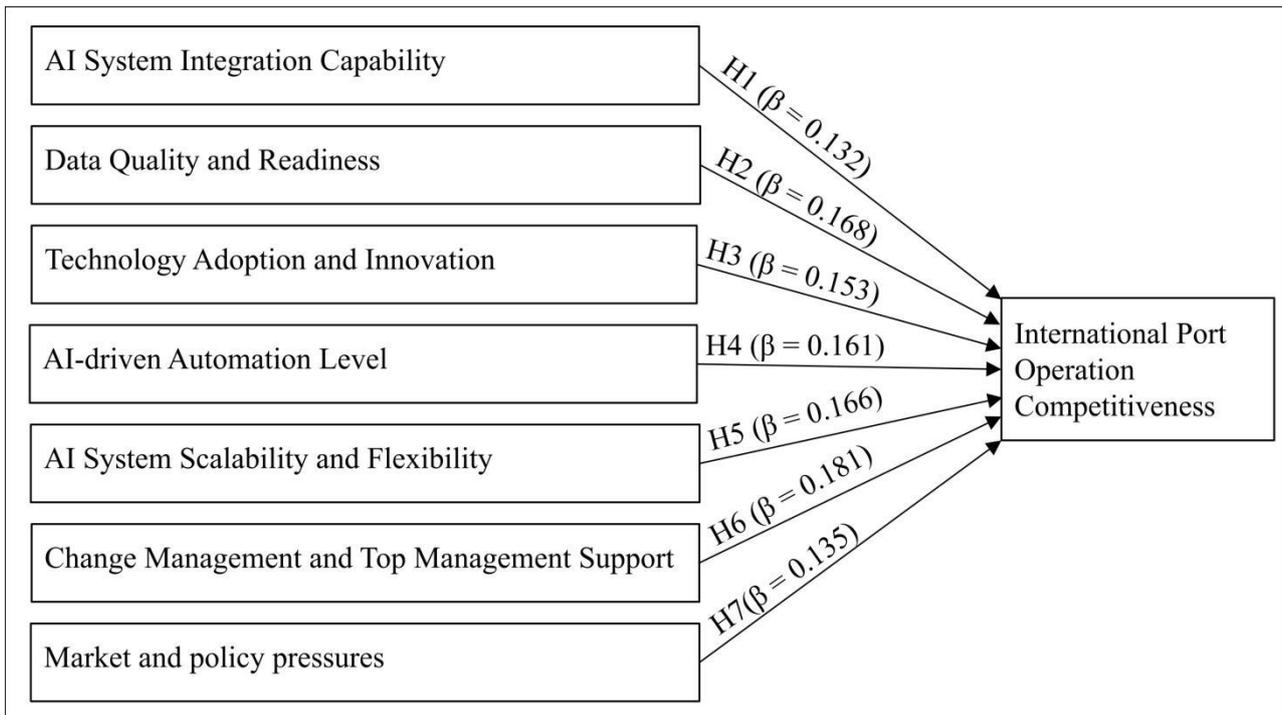


Figure 1: A Strategic Framework for International Port Operation Competitiveness.

## 6. Conclusions and Insights

### 6.1 Conclusion

Drawing upon the Technology-Organization-Environment (TOE) framework, this study systematically explored the pathways through which AI-driven digital transformation impacts international port operational competitiveness, based on a survey of 212 employees at BBW Port Group. The results confirmed that all seven independent variables exert a significant positive impact on competitiveness. Notably, organizational factors specifically change management and top management support demonstrated the most substantial influence, underscoring the critical role of leadership and systemic change strategies in the transformation process. Within the technological dimension, data quality, AI system scalability, and automation levels also exhibited strong explanatory power. Furthermore, market and policy pressures served as significant drivers within the environmental dimension. These findings suggest that enhancing port competitiveness requires the synergistic alignment of technological capabilities, organizational readiness, and external environmental adaptation.

### 6.2 Strategic Framework Development

Based on empirical research findings, this study constructs a three-tiered, phased digital transformation strategic framework, aiming to provide a clear path for the Beibu Gulf Port Group system to enhance its operational competitiveness. This framework first emphasizes organizational and governance transformation as the core driving force, requiring strong support from senior leadership and the establishment of a professional change management system to alleviate transformation resistance, cultivate an innovation-driven culture, and lay a solid foundation for the entire transformation process. Building on this, it is necessary to simultaneously strengthen the pillars of technology and data capabilities: prioritizing the construction of a unified data governance

platform to ensure data quality and availability; investing in modular and scalable technical architectures to support the efficient integration and flexible iteration of artificial intelligence applications; and gradually promoting the automation and intelligentization of key business processes. Furthermore, the port should proactively transform external market and policy pressures into strategic opportunities, actively align with industry standards and regulatory requirements, and leverage digital capabilities to expand ecological collaboration with supply chain partners, thereby enhancing the resilience of the entire network.

### 6.3 Research Limitations and Outlook

While this study verifies the mechanisms affecting port competitiveness within the TOE framework, certain limitations remain. First, concerning the sample scope, data were derived primarily from BBW Port Group employees. This relative homogeneity may limit the generalizability of the findings to other port contexts. Second, in terms of research design, the study utilized cross-sectional data, which effectively identified significant correlations between variables. However, this design constrains the assessment of causality and cannot fully capture the temporal evolution or long-term effects of digital transformation on competitiveness enhancement. These limitations highlight important avenues for future research, such as employing longitudinal designs or broader comparative studies.

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