Digital Technology–Enabled Intelligent Upgrading of Logistics Services at Dalian Port from the Perspective of Smart Ports

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Abstract: Dalian Port's logistics services face low efficiency, poor coordination, and limited value-added services. From a smart port perspective, this study proposes a "three-layer architecture and four-chain collaboration" framework enabled by digital technologies. Multi-scenario simulations show that digital empowerment reduces vessel turnaround time by 33%, increases quay crane efficiency by 39%, cuts per-container logistics costs by 18%, and raises the comprehensive intelligence index from 52.0 to 90.6. Practical countermeasures are provided for Dalian Port and similar ports.

Keywords: Smart Port; Digital Technology; Dalian Port; Logistics Services; Intelligent Upgrading

1. Introduction

Ports are critical to regional competitiveness, and smart ports have become a national priority. As a key gateway in Northeast Asia, Dalian Port suffers from low operational efficiency, poor information coordination, and limited value-added services. Digital technologies offer solutions, yet existing studies lack a systematic, quantifiable upgrading framework for Dalian Port. Following a "situation analysis–model construction–simulation verification–countermeasure suggestions" logic, this paper addresses three questions: How do digital technologies empower logistics services? How can an operable intelligent upgrading model be built? What are the effects and implementation pathways?

2. Theoretical Basis and Practical Analysis

2.1 Connotations of Smart Ports and Digital Technology Empowerment

A smart port is a new port form built on digital infrastructure and driven by data elements. Through IoT perception, network connectivity, and intelligent decision-making, it achieves collaborative optimization of port production, logistics, management, and services throughout the entire process, with general features of comprehensive perception, ubiquitous connectivity, data-driven operation, and intelligent collaboration. Digital technology empowers logistics services not by simple superposition of technologies, but by reconstructing the perception–decision–execution–service logic through data connectivity, transforming logistics services from passive response to active prediction, from segmented operations to whole-chain collaboration, and from basic service provision to value-added creation.

2.2 Current Situation and Pain Points of Logistics Services at Dalian Port

Based on an investigation of the logistics service processes of Dalian Port, its main pain points can be summarized into four dimensions, as shown in Table 1. These pain points are interwoven with one another. Localized technological improvements alone are insufficient to fundamentally solve these problems; instead, systematic reconstruction at the architectural level is urgently needed.

Table 1. Analysis of Pain Points in the Current Logistics Services of Dalian Port

Pain-point Dimension	Specific Manifestations	Limitations of the Traditional Model
Operational efficiency	Scheduling relies heavily on experience, and resource utilization is uneven.	Lack of real-time data and intelligent optimization.
Information coordination	Information systems among multiple stakeholders are fragmented, and document circulation is slow.	Data silos and lengthy coordination chains.
Service capability	Services are mainly limited to basic loading, unloading, and warehousing	Insufficient provision of value-added and integrated services.
Green and low-carbon	Energy consumption and emission management	Lack of refined energy-efficiency

development	remain relatively extensive	management tools.

2.3 Mechanisms of Digital Technology Empowerment

Digital technologies empower Dalian Port's logistics services through three mechanisms. First, the transparency mechanism uses IoT-based perception and digital twins to map physical operations into computable digital space, turning ambiguous operations into visible and controllable ones. Second, the optimization mechanism leverages big data and intelligent algorithms to jointly schedule berths, quay cranes, yards, and gates, improving operational efficiency. Third, the value-added mechanism enables end-to-end visibility, smart customs clearance, and supply chain finance through data connectivity and platform operations, upgrading service capacity. Together, these three mechanisms achieve cost reduction, efficiency improvement, value creation, and low-carbon development.

3. Construction of an Intelligent Upgrading Model for Logistics Services Empowered by Digital Technologies

3.1 Design Concepts and Principles

The construction of the model follows four principles.

First, it takes customer value and the enhancement of port service capacity as the core, ensuring that technology serves business objectives. Second, it emphasizes data connectivity, breaking down barriers among different stakeholders and realizing whole-chain collaboration. Third, it stresses layered architecture and loose coupling, ensuring that the system is scalable and capable of continuous evolution. Fourth, it focuses on practical implementation and replicability, ensuring that the upgrading pathway can be implemented in stages under the existing conditions of Dalian Port.

3.2 Intelligent Upgrading Framework of "Three-Layer Architecture and Four-Chain Collaboration"

Based on the enabling mechanisms, this paper constructs an intelligent upgrading framework characterized by vertical "perception layer–platform layer–application layer" support and horizontal "information chain–operation chain–service chain–decision-making chain" collaboration. The perception layer (5G, IoT, BeiDou, smart gates) enables real-time all-factor data collection; the platform layer (big data middle platform, digital twin, business middle platform) supports data governance, simulation, and capability accumulation; the application layer delivers intelligent scheduling, full-process visibility, smart customs clearance, and collaborative services. The four chains run through all layers: the information chain eliminates data silos, the operation chain optimizes production, the service chain expands value- added offerings, and the decision-making chain enables intelligent analysis. The overall structure is shown in Figure 1.

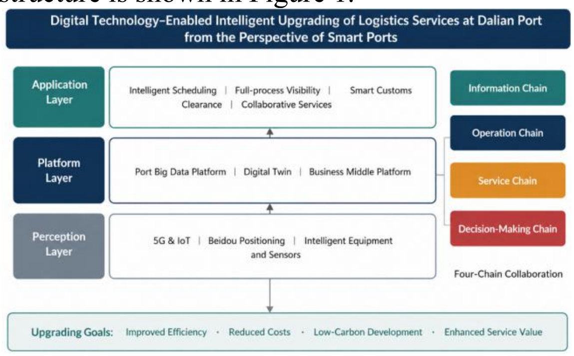

Figure 1. "Three-Layer Architecture and Four-Chain Collaboration" Framework for the Intelligent Upgrading of Logistics Services Empowered by Digital Technologies

3.3 Key Technical Support and Evaluation Model for Upgrading Effects

To quantitatively evaluate the effects of upgrading, this paper constructs a comprehensive evaluation model for logistics service intelligence. Let the comprehensive intelligence index SSS be composed of operational efficiency EEE, information coordination III, service capacity VVV, and green and low-carbon performance GGG, weighted as follows:

$$S = w^1 \cdot E + w^2 \cdot I + w^3 \cdot V + w^4 \cdot G \quad (1)$$

Where $w^1 \sim w^4$ are weight coefficients satisfying: $w^1 + w^2 + w^3 + w^4 = 1$, Based on expert consultation and the entropy weight method, this study sets $w^1 = 0.35$、$w^2 = 0.25$、$w^3 = 0.25$、$w^4 = 0.15$, All sub-indicators are normalized to a scale of $0 \sim 100$。Furthermore, the improvement in operational efficiency brought about by digital technology investment can be described by an efficiency improvement function with diminishing marginal returns:

$$E(d) = E^0 + \Delta E_{m}ax \cdot \left(1 - e^{(-\beta d)}\right) \quad (2)$$

Where E^0 denotes the baseline operational efficiency before upgrading, d 为 denotes the intensity of digitalization investment, $\Delta E_{m}ax$ denotes the upper limit of efficiency improvement, and β denotes the efficiency improvement elasticity coefficient.

The comprehensive upgrading benefit is measured by the difference between the comprehensive index before and after upgrading, expressed as: $\Delta S = S_{p}ost - S_{p}re$, This serves as the core indicator for evaluating the effectiveness of digital technology empowerment.

4. Simulation and Analysis of Upgrading Effects

4.1 Data Sources and Scenario Design

This study focuses on container and multimodal transport operations at Dalian Port. Based on publicly available statistics, industry benchmarks, and expert estimates, a parameter system is established. Five implementation stages (baseline, pilot, promotion, deepening, maturity) are defined to conduct multi-scenario simulations of the upgrading framework. Under unchanged cargo volume structure and operational capacity constraints, only the intensity of digital technology investment and coordination level are varied to isolate the net effect of digital empowerment.

4.2 Analysis of Upgrading Effects

Figure 2 shows the comparison of the key logistics performance indicators before and after the intelligent upgrading. Taking the pre-upgrading level as the base value of 100, the average vessel turnaround time in port is decreased to 67 after upgrading, the quay crane hourly operating efficiency rises to 139, the yard turnover rate rises to 125, the document processing time decreases to 19, and the comprehensive logistics cost per container decreases to 82. The above results show that the operation efficiency is improved a lot and the cost has been reduced a lot.

Figure 3 shows the changes of the comprehensive logistics service intelligence index in different implementation stages from the evolution view. Under the digital technology -enabled upgrading pathway of Dalian Port, the comprehensive index increases gradually from the baseline value of 52.0 to 90.6 at the maturity stage through the pilot, promotion and deepening stages. And under the traditional upgrading pathway, the index only rises from 52.0 to 61.2 in the same period. The gap between the two paths keeps to widen in the process of the implementation stages. It means that the effect of digital technology empowerment in the increase of logistics service capacity is significant and sustainable.

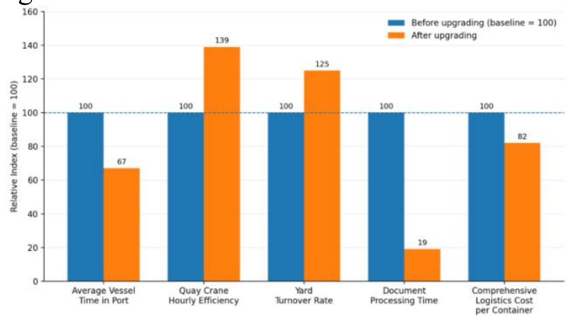

Figure 2. Comparison of Key Logistics Performance Indicators Before and After Intelligent Upgrading

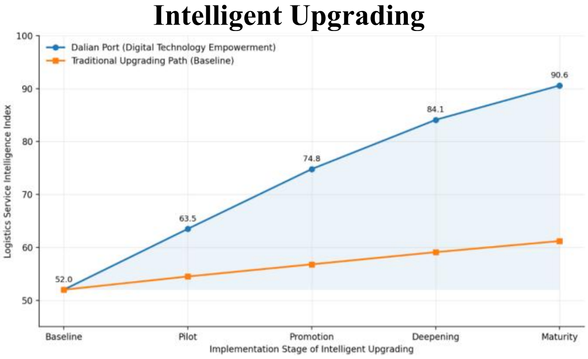

Figure 3. Evolution Curve of the Comprehensive Logistics Service Intelligence Index Across Implementation Stages

The comparison of key comprehensive indicators is shown in Table 2. Digital technology empowerment significantly outperforms the traditional upgrading pathway in terms of efficiency, cost, coordination, and the comprehensive index, thereby verifying the effectiveness and superiority of the proposed upgrading model.

Table 2. Comparison of Key Indicators Before and After Digital Technology Empowerment

Evaluation Indicator	Before Upgrading	After Upgrading	**Change**
Average vessel time in port / h	28.5	19.2	−32.6%
Quay crane hourly efficiency / boxes	28.4	39.5	+39.1%
Yard turnover rate (relative)	100	125	+25.0%
Comprehensive	100	82	−18.0%

logistics cost per container (relative)			
Comprehensive intelligence index / S	52.0	90.6	+38.6

4.3 Comprehensive Evaluation

The simulation results show that the "three-layer architecture and four-chain collaboration" framework can effectively break through data barriers, optimize resource allocation, and expand value-added services. As a result, the logistics services of Dalian Port achieve systematic improvement in terms of efficiency, cost, coordination, and green development.

At the same time, the analysis also indicates that the upgrading effect shows a pattern of diminishing marginal returns. In the transition from the deepening stage to the maturity stage, the rate of improvement tends to slow down. This suggests that, in the later stages of upgrading, greater attention should be paid to ecosystem collaboration and service model innovation rather than simply increasing technological investment.

5. Countermeasures and Suggestions

To upgrade Dalian Port's logistics services intelligently, four measures are proposed. First, build a big data middle platform and digital twin with unified data standards to break silos. Second, apply 5G, AI, and IoT in smart scheduling, yards, and gates through phased implementation. Third, develop a collaborative port-shipping ecosystem and value-added services (e.g., supply chain finance) to shift from a loading hub to a supply chain organizer. Fourth, improve data security, performance evaluation, and interdisciplinary talent cultivation. An implementation mechanism of "pilot demonstration–evaluation–phased promotion" with dynamic adjustment should also be adopted.

6. Conclusions and Prospects

This paper explores digital technology-enabled intelligent upgrading of Dalian Port's logistics services. Three conclusions are drawn: digital technologies address inefficiency, poor coordination, and limited services through transparency, optimization, and value creation; the "three-layer architecture and four-chain collaboration" framework offers an operable pathway; simulations show vessel time reduced by 33%, quay crane efficiency up 39%, per-container cost down 18%, and intelligence index rising from 52.0 to 90.6. Future research should incorporate granular data, expand to more business scenarios, and include carbon emission and resilience indicators to support green and resilient port development.

Acknowledgements

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