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Digital Twin Technology Drives Real-Time Scheduling Optimization for Port Container Operations: A Verification Study Centred on the Goals of Efficiency Improvement and Cost Control

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Abstract

In the context of global port intelligent transformation, digital twin technology has become a key support for breaking through the bottleneck of container operation scheduling efficiency and reducing operational costs. This study adopts a single-case exploratory design, selecting typical ports that have deployed digital twin systems as the research objects. It systematically examines the application mechanism of digital twin technology in container operation scheduling from three dimensions: technical empowerment, decision reconstruction, and performance optimization. The research team obtained multiple data sources through field investigation methods such as participatory observation, system operation logs, scheduling record reports, and in-depth interviews. They used the three-level coding method of grounded theory to construct a process model of "technical empowerment - decision transformation - performance output", revealing the complete transformation path from technical input to efficiency-cost dual-target output. The study found that the digital twin system realizes real-time integration and virtual mapping of all process data through a hierarchical architecture, forming a hierarchical human-machine collaborative decision-making model of "automated in routine scenarios, collaborative in complex scenarios, and manual in emergency scenarios", effectively achieving the collaborative optimization of vessel operation efficiency and reduction of operational costs. The process model constructed in this study reveals the internal mechanism of digital twin technology driving scheduling optimization, providing systematic theoretical and practical guidance for the construction of intelligent port scheduling.

Keywords

digital twin technology, port container operation scheduling, human-machine collaborative decision-making

1. Introduction

With the acceleration of the global supply chain integration process, the core position of ports as logistics hubs has become increasingly prominent. According to the United Nations Conference on Trade and Development, approximately 80% of global trade volume is completed by sea transportation, and ports are the key nodes in this transportation chain [1]. As the world's largest trading nation, China completed 310 million standard container throughput at its national ports in 2023, with a year-on-year growth of 4.9% [2].

The continuous increase in container throughput has brought significant pressure to port operation scheduling: The traditional scheduling model relies on manual experience, which has problems such as information asymmetry, delayed decision-making, and unbalanced resource allocation, resulting in long vessel stay times, low equipment utilization, and high operating costs [3].

In this context, digitalization and intelligence have become the inevitable trend for port transformation. Digital twin technology, as a key technology to connect the physical world and the virtual space, can achieve real-time mapping of all elements of the operation scenario, multi-dimensional simulation and planning, and dynamic optimization decision-making, providing a new solution for port scheduling optimization [4]. This study focuses on the application mechanism of digital twin technology in port container operation scheduling, aiming to answer the core question of “How does digital twin technology drive the real-time scheduling optimization of port container operations and achieve the dual goals of efficiency improvement and cost control”? The research is mainly conducted from three aspects: technology empowerment, decision reconstruction, and performance optimization, and uses the grounded theory three-level coding method to systematically analyse multiple data sources such as participatory observation, system operation logs, and scheduling record reports. The study selects typical ports that have deployed digital twin systems as case objects, conducts field investigations, and forms triangulation verification through multiple data sources to ensure the credibility of the research conclusions

2. Literature Review and Theoretical Foundation

2.1 Digital Twin Technology and Its Application Research

The concept of digital twin was first proposed by Professor Grieves in 2003. Its core lies in achieving dynamic management of the system throughout its entire life cycle through the organic integration of physical entities, virtual models, and data links [3]. Tao et al. further proposed a five-dimensional structural model of digital twin, covering physical entities, virtual entities, connections, data, and services, providing a theoretical framework for the system construction of digital twin [5]. Tao Fei et al. conducted a systematic analysis and reflection on digital twin technology from a more macroscopic perspective [6]. In the port field, Neugebauer et al. conducted a systematic review of the application status, implementation paths, and decision-support value of digital twin in container terminal scheduling through global port case analysis [7], while Kastner et al. focused on the practical application and optimization path of digital twin technology in improving the operational efficiency of container terminals and carried out empirical research [8]. Zhang et al. explored the development direction of smart ports from the perspective of human-machine collaboration [9]. However, existing studies mostly focus on technical architecture design or optimization of a single link, lacking systematic examination of the entire scheduling process, and research on how digital twin is embedded in the scheduling decision-making process and its impact on the human-machine collaboration model is still relatively rare [8,9].

2.2 Research on Container Terminal Scheduling Optimization in Ports

Container terminal scheduling optimization has always been a research hotspot in the fields of logistics and operation management. Steenken et al. conducted a systematic review of the optimization problems of terminal operations, dividing the problems into berth allocation, crane scheduling, truck routing, and yard allocation, etc. [10]. Carlo et al. further analysed the coupling relationships among the sub-problems, indicating that integrated optimization is the key to improving overall efficiency [11]. In terms of scheduling methods, early studies mainly relied on mathematical programming and heuristic algorithms [12]. The relevant review studies have clearly demonstrated that the simulation optimization method has become the mainstream technical approach for the integrated planning of berth allocation and quay crane scheduling. [12]. In recent years, research has gradually evolved towards the integration of “technology + algorithm”, and relevant studies have pointed out that real-time data-driven and intelligent algorithm integration is the future development direction [9,13]. However, such research mostly remains at the level of theoretical modelling and lacks deep integration with actual operation scenarios, ignoring the collaborative relationship between human decision-making and the technical system.

2.3 Research on Human-Machine Collaborative Decision-Making

Human-machine collaborative decision-making is a core issue in the application of intelligent systems. Parasuraman et al. proposed a hierarchical model of human-machine function allocation, dividing human-machine responsibilities into four stages: information acquisition, analysis, decision-making, and action [13]. In the field of automated systems, studies have shown that as the level of automation increases, the role of humans shifts from operators to supervisors [9]. In the field of operation management, studies have shown that the key to human-machine collaborative decision-making lies in "mutual trust" and "explainability" - the system needs to be able to explain the logic of its recommended solutions, and operators need to understand the boundary of the system's capabilities [13].

2.4 Review of Research and Positioning of This Study

In summary, the existing research has the following gaps: First, the application research of digital twin in port scheduling mostly remains at the level of architecture design and simulation verification, lacking in-depth analysis of the interaction mechanism between technology, people, and performance in actual applications; second, there is relatively little research on how digital twin reshapes the scheduling decision-making process and affects the human-machine collaboration mode; third, there is a lack of field investigation and grounded theory analysis based on real scenarios, making it difficult to construct a process theory with explanatory power. This study intends to use a single-case exploratory design and the grounded theory analysis method to fill these research gaps.

3. Research Design

This case selects a core hub container port with a capacity of over 10 million TEUs in the domestic coastal area as the research object. This port implemented the world's first comprehensive digital twin technology platform for ports in 2022 and continuously iterated and upgraded the real-time scheduling system of digital twin container operations. The background of its construction, technical architecture, and application process all conform to the common characteristics of China's port digital transformation, and have typical research and reference value. The traditional scheduling mode of this port adopts an operation mode of "manual experience + local system assistance", and has long faced common industry pain points such as information asymmetry, data silos, and delayed decision-making. There are problems such as mismatch of berth and crane resources, high empty driving rate of forklifts, and lack of forward-looking planning of the storage yard box positions. To solve these problems, the port built an operation real-time scheduling system based on digital twin technology, promoting the transformation of the scheduling mode from "manual experience-led" to "human-machine collaborative intelligent decision-making".

3.1 Technology Empowerment

The digital twin container operation scheduling system of this port adopts a standardized hierarchical architecture of perception layer - transmission layer - modelling layer - application layer. In the perception layer, the system collects multi-source data such as vessel arrival dynamics, crane operation status, forklift positions, and storage yard box allocation through nodes such as Beidou positioning, equipment sensors, and video surveillance, achieving full-process real-time collection of data. This solves the problem of incomplete data collection and poor real-time performance in traditional scheduling. In the transmission layer and modelling layer, the system eliminates "data silos" through data standardization cleaning, heterogeneous data fusion, and real-time data graph construction. At the same time, it builds a high-precision virtual twin model that matches the physical port 1:1, achieving millisecond-level real-time mapping of physical operation scenarios and virtual models. In the application layer, the system develops five core functional modules: berth intelligent allocation, crane operation scheduling, forklift path optimization, storage yard box planning, and scenario simulation and planning, integrating the port's self-developed new generation container terminal control system, and possessing three core capabilities: full-process real-time mapping, multi-scenario simulation planning, and intelligent generation of scheduling plans.

3.2 Decision Reconfiguration

The implementation of the digital twin scheduling system has promoted the decision-making mode to transform from the traditional “single decision based on manual experience” to a hierarchical human-machine collaborative decision-making mode with different levels. In the early stage of system application, the decision-making mode was mainly “manual guidance + system information support”, and the dispatcher relied on their own experience to formulate plans. As the application deepened, the dispatcher's trust in the system gradually increased, forming a clear hierarchical operation logic: in routine operation scenarios, the system automatically generates a complete set of scheduling plans, and the dispatcher only needs to conduct compliance review and confirmation; in complex operation scenarios, the system simulates different plans through the virtual twin model, and the dispatcher combines experience for local optimization and adjustment, achieving “system scientific simulation + human experience judgment” for efficient collaboration; in emergency operation scenarios, the dispatcher initiates manual-led decision-making, and the system provides key data support in real time. After long-term integration, the dispatcher's role has transformed from “plan maker” to “plan reviewer and complex scenario optimizer”, and the system has taken on a large amount of standardized scheduling work, achieving complementary advantages between humans and machines.

3.3 Performance Optimization

The application of the digital twin scheduling system has promoted the efficiency improvement and cost control of container operations at the port. At the operation efficiency level, the system achieves a complete solution to the problem of information asymmetry through full-process real-time mapping and global data integration, effectively alleviating the phenomenon of resource mismatch. After the core intelligent terminal of the port implemented this system, the time for container pick-up and delivery in port has significantly decreased, the efficiency of ocean-going artery vessels when at berth has significantly improved, the operational continuity of core equipment such as cranes and forklifts has significantly enhanced, and the ineffective waiting time of equipment has been significantly reduced. In terms of operational costs, the ineffective operation rates of core equipment such as gantry cranes and container trucks have significantly decreased, effectively reducing the energy consumption per unit of operation for the equipment; the system has taken on a large amount of standardized scheduling tasks, significantly reducing the costs of manual communication and coordination in the scheduling process, and avoiding the problem of redundant manpower. From the perspective of the logic of collaborative optimization, the port has achieved global visualization and precise control of the entire operation process through digital twin technology, and optimized the operation process and reduced ineffective.

3.4 Data Analysis Process

This study follows the three-level coding path of grounded theory. In the open coding stage, the original data such as observation logs, system operation logs, and interview transcripts are analysed sentence by sentence to extract 57 initial concepts, which are then merged into 18 initial categories. In the main axis coding stage, the 18 initial categories are integrated into 5 core categories: technology empowerment, decision-making model, collaborative evolution, efficiency performance, and cost performance. In the selection coding stage, “digital twin-driven scheduling optimization” is selected as the core category, and the “process model of digital twin-driven scheduling optimization” is constructed. The analysis process is independently conducted by two members and compared regularly, and the saturation of the model is verified by the reserved original data.

4. Research Findings

The research found that the digital twin scheduling system adopts a hierarchical architecture, enabling real-time data collection and integration for the core operational processes. At the data collection level, the system achieves the fusion of multi-source heterogeneous data through standardized processing; at the real-time mapping level, the system builds a high-precision virtual port model to reflect the location, status, and operation progress of physical entities in real time; at the simulation and planning level, the system conducts scenario simulation and pre-planning based on real-time data. The integrity of data integration, the fidelity of model mapping, and the timeliness of simulation and planning are the key elements determining the effectiveness of technology empowerment. After the system is deployed, a “system assistance - human-machine collaboration” decision-making model is formed: in routine scenarios, automated decision-making is carried out by the system, which automatically generates scheduling plans, and the dispatcher reviews and confirms; in complex scenarios, collaborative decision-making is conducted by the system, the simulation effect of the plan is considered by the dispatcher, and the decision is optimized based on experience; in emergency scenarios, manual-led decision-making is initiated by the dispatcher, and the system provides data support. As the system application deepens, the dispatcher's trust in the system gradually increases, the boundaries of human-machine responsibilities become increasingly clear, and a stable hierarchical decision-making model is formed. Based on the performance data analysis using the observation index system, the results show a significant collaborative optimization relationship between efficiency and cost. In terms of efficiency, the average operation time of ships is shortened, and the utilization rate of gantry cranes is improved; in terms of cost, the unit operation energy consumption of equipment decreases, and the efficiency of human resource allocation improves. The system optimizes the operation process, reduces equipment ineffective operation, improves efficiency while reducing energy consumption; through precise resource allocation, it shortens the operation response time and improves resource utilization, achieving a win-win situation of efficiency and cost.

5. Theoretical Model Construction

Based on the coding analysis of grounded theory, this study constructed the “process model of digital twin-driven port scheduling optimization”, revealing the complete transformation mechanism from technical input to performance output. Technological empowerment is the fundamental part of the model. The digital twin system, through real-time collection, integration of multi-source data and high-precision virtual simulation, provides the basic support for scheduling optimization. Data integration achieves transparency and visualization of the entire operation process, eliminating information asymmetry; simulation and deduction can predict the effects of different scheduling schemes in advance, reducing decision-making risks. Decision transformation is the core mechanism of the model. Technological empowerment realizes value transformation through decision model innovation, and the digital twin system changes the traditional single mode of manual decision-making, forming a human-machine collaborative decision-making mechanism that adapts to different scenarios: routine scenarios are automatically processed to improve efficiency, complex scenarios are jointly processed to balance scientific and flexibility, and emergency scenarios are led by humans to ensure safety. Performance output is the ultimate goal of the model. Human-machine collaborative decision-making ultimately promotes the coordinated optimization of efficiency and cost targets, by optimizing the operation process and rationally allocating resources, achieving the dual goals of efficiency improvement and cost reduction, forming a complete closed loop of “technology empowerment - decision optimization - performance improvement”.

6. Conclusion

The research results of this study are as follows: The digital twin technology realizes the real-time integration and virtual mapping of the entire process of port container operations through a hierarchical architecture, forming a hierarchical human-machine collaborative decision-making model, effectively promoting the collaborative optimization of operational efficiency improvement and cost reduction. Thus, the research conclusion drawn is that the complete transformation mechanism of digital twin-driven scheduling optimization can be summarized as a process model of “technology empowerment - decision transformation - performance output”, and the three elements form a closed-loop iterative optimization path. This study provides valuable reference significance for future research, mainly influencing the theoretical explanation of the application mechanism of digital twin in the port scheduling field, expanding the analysis framework of the human-machine collaborative decision-making model, and revealing the conditions for achieving dual-objective collaborative optimization of efficiency and cost. Future research should focus more on comparative studies of multiple cases to test the applicability and boundary conditions of the model, and conduct longitudinal tracking studies to observe the long-term evolution effect of technology application.

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Conflicts of Interest

The authors declare no conflict of interest.

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