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Review on Intelligent Scheduling and Operation Optimization of Container Terminals Empowered by Digital Twin

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Abstract. Container terminals, handling over 80% of global trade, face a "triple dilemma": complex multi-equipment coupling, frequent disturbances, and stringent international carbon mandates like the IMO policies and EU ETS. Traditional optimization methods struggle with real-time adaptation and low-carbon compliance. Digital Twin (DT) technology offers a new paradigm for virtual–physical mapping and carbon efficiency management. This paper systematically reviews port digital twins and intelligent scheduling, constructing a four-dimensional framework: architecture, problems, technologies, and applications. Findings indicate that DTs are characterized by bidirectional closed-loop interaction, with a four-layer architecture becoming the mainstream paradigm. While scheduling models for multi-equipment collaboration are maturing, the research frontier has shifted toward DT-driven uncertainty rescheduling and low-carbon strategies, such as equipment ratio optimization and charging management. Core technologies—data fusion, virtual modeling, and reinforcement learning—are increasingly robust. Practical implementations in major hubs like Qingdao and Yangshan ports demonstrate that DT solutions significantly enhance operational efficiency and reduce emissions. Ultimately, DT technology provides a critical pathway for terminals to navigate international carbon regulations and achieve green, high-quality development.

Keywords: Digital Twin, Container Terminal, Intelligent Scheduling Multi-Equipment Collaboration, Green and Low-carbon Operation

1. Introduction

Container terminals, as critical nodes in global trade and supply chains, undertake over 80% of international cargo transportation. They serve as pivotal hubs ensuring seamless global trade and integrating maritime and land transport systems. Confronted with trends such as vessel enlargement and shipping alliances, terminal operations face multiple pressures, including complex multi-equipment coordination, frequent, unpredictable disruptions, and increasingly stringent carbon-emission constraints. The operations of quay cranes, automated guided vehicles (AGVs), and rail-mounted gantry cranes (RMGs) are tightly coupled. Furthermore, interference between dual automated stacking cranes (ASCs) increases scheduling complexity, while disruptions like fluctuating truck arrivals and equipment failures often render static scheduling ineffective [1]. Against the backdrop of the "dual carbon" goals, low-carbon retrofitting of terminal equipment has

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become an urgent necessity. Traditional methods, such as mixed-integer programming and offline simulation, have been widely studied [2]. However, their reliance on static assumptions and lack of real-time closed-loop control make them struggle to adapt to dynamic disturbances [1,3]. In contrast, digital twin technology, through bidirectional high-fidelity virtual-physical mapping, offers a novel approach to tackling these challenges and enabling closed-loop scheduling [3]. Core functionalities of digital twins—including real-time mirroring, simulation-based deduction, and closed-loop optimization—effectively address four key challenges in container terminals: multi-equipment coordination, dynamic rescheduling, yard optimization, and green scheduling. This study employs a systematic literature review methodology to analyze existing research. Identifying gaps in current reviews, this paper, for the first time, positions "twin-enabled scheduling" as an independent interdisciplinary field. By integrating relevant architectures and models, it fills the research gap in systematic synthesis within this domain, providing theoretical references and directional guidance for future studies.

2. Theoretical basis of digital twin and port application architecture

2.1. Conceptual connotation and evolution

The conceptual origin of digital twins can be traced to Grieves' "Mirror Space Model", introduced in 2002 [4]. In 2012, NASA further defined the concept as a high-fidelity virtual representation of an aircraft or system [3]. Neugebauer et al. [3] draw a clear conceptual distinction among digital models, digital shadows, and digital twins: digital models involve unidirectional manual data flows; digital shadows enable automated data flows from the physical to the virtual domain; digital twins, by contrast, feature bidirectional, fully automated data flows between the virtual and physical systems, enabling closed-loop control.

2.2. Digital twin architecture for ports

The five-dimensional model proposed by Grieves and Vickers (physical entities, virtual entities, connections, data, and services) serves as the theoretical foundation for digital twins [3]. Neugebauer et al. adapted this framework to port scenarios [3]: Physical layer: encompasses all essential resources, including quayside cranes, automated guided vehicles (AGVs), and vessels [5,6].

Virtual layer: incorporates high-precision geometric models along with kinematic and physical models describing equipment behavior.

Connection layer: enables data acquisition and control through technologies like 5G and industrial Ethernet [3].

Data layer: integrates multi-source heterogeneous data such as Time-of-Service (TOS), Real-Time Control Management System (RCMS), and Global Positioning System (GPS) [5,6]; Service layer: integrates functionalities including real-time monitoring, simulation modeling, and intelligent scheduling [5,6].

Based on the research by Wen Jiahua [6] and Wang Gengyu et al. [5], digital twin systems for container terminals typically adopt a four-tier technical architecture: the physical layer (infrastructure and equipment), data layer (data collection, cleaning, and storage—such as hybrid storage solutions like SQL Server + Redis [5]), model layer (including geometric, kinematic, and operational logic model libraries [5]), and service layer (providing visualization and scheduling applications tailored for different roles).

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2.3. Current status and maturity of domestic and international applications

International leadership: Hamburg Port achieves automated traffic signal control and bridge health prediction through a "digital twin test bed"; Antwerp Bruges Port integrates BIM, AIS, and meteorological data to support pollution traceability and drone inspections.

Singapore Port applies simulation optimization to layout design and AGV charging strategies[3].

Domestic advancements: Shanghai Yangshan Port Phase IV integrated ECS data to achieve full-process 3D visualization and operational playback [7,8]; Qingdao Port utilized Unity 3D to construct virtual environments for AGV dynamic scheduling and path planning [8,9]; The Nansha Phase IV Fully Automated Container Terminal at Guangzhou Port has established a "5G+Beidou" automated terminal operation system, achieving intelligent scheduling and unmanned operations for containers throughout the entire process from shore to storage yard.

Maturity gradient: Leading ports have achieved closed-loop optimization; catch-up ports focus on single-scenario validation; a large number of small and medium-sized ports remain at the basic digitalization stage [3].

2.4. Core functional spectrum

The digital twin functionality of ports can be categorized into four levels:

Real-time Mirror Layer: 3D visualization for panoramic job replication, supporting status queries and playback [5,9]; Simulation and Simulation Layer: Built-in discrete event simulation engine enabling "what-if" analysis [7,10]; Prediction and Early Warning Layer: Utilizes machine learning to predict equipment lifespan and container truck arrival times.

Optimization and Control Layer: Generates operational plans through operations research optimization and implements closed-loop execution [1,10].

Currently, the vast majority of systems remain at the first two tiers.

3. Classification of core issues in intelligent scheduling for container terminals

3.1. Multi-device collaborative scheduling

Research on Integrated Scheduling of Terminal Crane-AGV-Pile Yard Crane Systems: Jonker et al. [10] modeled the process as a four-stage hybrid assembly line, introducing "operation pairing" constraints to characterize dual-container handling operations. Luo et al. [2] combined AGV task allocation with pile yard container positioning for joint optimization, effectively reducing vessel berthing time. Cao et al. [9] further incorporated bidirectional AGV route planning into the model, proposing a two-layer differential evolution algorithm to optimize task allocation and conflict-free path planning jointly.

Interference avoidance in dual automated stacker systems: Xiao Long et al. [11] identified four interference patterns. By adopting a handshake zone configuration scheme, cross-container operations were decomposed into multiple subtasks for sequential execution. Compared with fixed schemes, optimal handshake zone positioning reduces operational completion time [11].

Rail-water multimodal transport coordination: Li et al. [1] developed a multi-device collaborative scheduling model for railway central stations with independent yard layouts, encompassing rail cranes, internal/external container trucks, and six types of container flows.

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3.2. Uncertainty scheduling and rescheduling

Sources of uncertainty primarily include three categories: task arrival, operational efficiency, and equipment availability [1].

Re-scheduling strategy: Li et al. [1] proposed a hybrid strategy combining "active response" and "global-local" approaches. Global re-scheduling employs a dual-trigger mechanism based on cycle duration and deviation thresholds; the local recovery strategy is categorized into four sub-strategies according to device status (maintaining original queue order or FCFS preemptive scheduling during idle periods, and preserving assigned queues or performing nearest-reassignment during active periods) [1].

Elastic scheduling driven by charging strategies: Numerical experiments conducted during Phase IV of Guangzhou Nansha Port show that the proposed dual-threshold charging strategy outperforms the existing single-threshold strategy. By introducing an additional judgment condition for stopping charging, the dual-threshold strategy makes AGV scheduling more resilient. AGVs can start or stop charging in real time based on task battery requirements and queuing status, enabling staggered charging to allow other AGVs to make the best use of available time to complete tasks [12]. Gao et al. [13] integrated battery health prediction into digital twins, dynamically adjusting charging timing through Q-learning to reduce completion time .

3.3. Optimization of yard operations

Storage location allocation: Peng et al. [14] introduced carbon emission constraints into the location allocation model to reduce the driving distance of inner circles .

Crane task scheduling in stockyards: Mi Chao et al. [7] validated the ECS system's response to quay crane failures through fault injection testing. After optimization, quay crane efficiency declined slightly during busy operations, accompanied by a moderate increase in waiting times for container handling, lifting, and external trucks [7].

3.4. Green and low-carbon scheduling

Relationship between equipment configuration and carbon emissions: Peng et al. [14] systematically quantified the correlation between equipment configuration and carbon emissions. When the ratio of quay cranes: yard cranes: internal car carriers increased from 1:2:3 to 1:2:4, ship emissions in port decreased by 35.3%, while total terminal emissions dropped by 22.8% [14]. A comparison by Yang and Lin [15] demonstrated that automated loading/unloading equipment reduced carbon emissions by 65.53% compared to manual handling systems.

4. Key technologies for dispatch optimization empowered by digital twin

4.1. Multi-source data perception and fusion

Port data sources comprise four layers: device layer (PLC/ECS status), operation layer (TOS services), environmental layer (meteorological data and AIS), and positioning layer (GPS/Beidou) [3,5,6]. Wang Gengyu et al. [5] adopted a hybrid storage architecture combining SQL Server, Redis, and MongoDB to handle multi-source heterogeneous data. Cao et al. [9] developed a timestamp-based path segment reservation mechanism that updates AGV status every 100 milliseconds. Li et al. proposed an event-triggered dual-synchronization mechanism [1] that can significantly reduce network bandwidth utilization.

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4.2. Virtual modeling and simulation inference

Geometric modeling: Wen Jiahua [6] detailed the methodology for constructing 1:1 scale 3D wharf models using 3ds Max and Unity 3D.

Behavioral and physical modeling: Gao et al. [11] developed a state-machine model for AGVs; Song et al. [12] proposed a nonlinear charging model for lithium batteries.

Semi-physical Simulation and Fault Injection: The semi-physical simulation architecture proposed by Mi Chao et al. [7] categorizes 16 common fault types. By configuring fault quadruples for parameterized injection, it validates ECS's fault-tolerance capability [7].

4.3. Intelligent optimization algorithm integration

Exact algorithms: Luo et al. [2] and Li et al. [1] employed Gurobi to solve small-scale problems, validating the solution quality of meta-heuristic algorithms.

Meta-heuristic algorithms: Genetic algorithms [2,11], particle swarm optimization [1], differential evolution [9], and simulated annealing [10] have been widely applied, with simulated annealing supporting quasi-real-time scheduling at 8-terminal bridge scale [10].

Reinforcement learning: Gao et al. [11] modeled AGV scheduling as a Markov Decision Process (MDP) and employed Q-learning for optimization, achieving a reduction in completion time [13].

Rule-based approach: Kong Weiwei et al. [8] summarized nine common AGV scheduling rules. Li et al. [1] adopted First-Come, First-Served (FCFS) and nearest-reassignment rules in local recovery strategies, effectively suppressing disturbance propagation [1].

4.4. Visualization and human- computer interaction

3D visualization represents the most intuitive manifestation of digital twin value [5,8]. Wen Jiahua [6] utilized multi-screen splicing to display panoramic port views. Wang Gengyu et al. [5] implemented environmental rendering modules to achieve dynamic lighting effects for dawn/dusk transitions and weather simulations. Zhang Yong et al. [16] emphasized that visualization's core lies in transforming data into intuitive representations, such as equipment status coloring and heat maps for operational progress. These systems typically integrate data dashboards to centrally present Key Performance Indicator (KPI) metrics.

5. Application scenario of scheduling optimization driven by digital twin

Digital twin technology elevates scheduling optimization from 'offline planning' to 'dynamic adaptive regulation,' with its core application scenarios focusing on equipment efficiency, collaborative capability, disturbance resilience, and low-carbon objectives.

In AGV scheduling, the bidirectional transportation mode demonstrates superior operational efficiency compared to the unidirectional mode, while keeping CPU time within a reasonable range. This mode shortens AGV travel paths for container transportation between the vessel and yard handling areas, thereby reducing energy consumption and equipment wear, and improving the management level of the multi-AGV system [9]. Additionally, an effective charging strategy enhances operational efficiency by reducing AGV idle time, charging duration, and charging wait time. It also ensures efficient coordination with quay cranes and yard cranes, leading to improved operational performance, particularly in automated terminals [12].

In sea-rail intermodal scenarios, the DT-enhanced rescheduling method minimizes start time deviations and overall task deviation, outperforming both traditional rescheduling and a no-

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rescheduling baseline. By interleaving tasks from different container flows and scheduling them rationally, the overall maximum task completion time is effectively reduced. A periodic rescheduling strategy further reduces queuing and ensures the timely execution of subsequent tasks [1].

6. Conclusion

This study focuses on intelligent scheduling and operational optimization of container terminals empowered by digital twins, systematically reviewing existing research across four dimensions: theoretical framework, problem classification, key technologies, and application scenarios. Theoretically, digital twins distinguish themselves from paradigms like digital shadows through their bidirectional virtual-real closed-loop control capabilities, with port applications demonstrating a maturity gradient evolving from visualization to closed-loop optimization. In terms of problem classification, multi-device collaborative scheduling forms a complete modeling system, while uncertainty-driven re-scheduling strategies are advancing toward digital twin-powered approaches. Stack repositioning problems have been proven to be NP-hard, and equipment allocation strategies with charging protocols provide quantitative approaches for green scheduling. Technologically, hybrid storage systems, event-triggered mechanisms, semi-physical simulation, and meta-heuristic algorithms have reached maturity, with reinforcement learning and 3D visualization technologies gradually being implemented. In practice, solutions such as automated guided vehicle (AGV) scheduling and centralized dispatching have demonstrated effectiveness at Qingdao Port and Yangshan Port. This study theoretically constructs a "problem-model-technology-application" quadri-dimensional framework, filling gaps in digital twin and scheduling research syntheses while offering practical references for port optimization and green transformation. However, limitations, including port operational complexity, fragmented research findings, and limited enterprise implementation disclosures, restrict the study's coverage in literature synthesis, cross-language analysis, and emerging technology integration. Future research should deepen exploration into agent-based twin architectures, distributed collaborative decision-making, human-machine interactive decision-making, explainable algorithms, lifecycle digital infrastructure, and energy-carbon dual-control scheduling. Digital twins are driving port scheduling systems from offline simulations to intelligent closed-loop operations, positioning them as core infrastructure for efficient, resilient, and sustainable global supply chain operations.

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