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Research on Port Container Congestion Relief Strategies under Multimodal Transport

Fugang Meng

Jiuhua Group Co., Ltd., 100090, Beijing, China

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Abstract: The essence of container congestion at ports in multimodal transport systems is the systematic outbreak of the triple contradictions of rigid infrastructure, information silos and lagging systems. Research shows that the deep-seated root cause lies in the topological complexity of the multimodal transport network (multi-level coupling of sea, land and air), the spatio-temporal heterogeneity of traffic (sudden peaks and regional imbalances), and the conflict of main objectives (local optimization leading to global suboptimization). This paper proposes a "technology - system" dual-dimensional governance framework: At the technical level, a real-time mapping system for the physical and virtual aspects of the port is constructed through digital twins to achieve dynamic optimization of the storage yard. Researchers should adopt federated learning to overcome cross-agent data barriers and establish privacy-preserving collaborative decision-making mechanisms. Developers must reconstruct the document trust ecosystem using blockchain technology to ensure full-chain verifiability. Policymakers ought to design dynamic congestion pricing schemes and cross-domain governance protocols to equitably balance multi-stakeholder interests. Empirical evidence shows that digital twins have increased the turnover efficiency of storage yards by 40% and reduced the processing time of blockchain documents by 80%. The research provides a theoretical paradigm and technical path for breaking the "congestion - inefficiency" cycle.

1. Introduction

Under the background of global supply chain reconstruction, as the core hub of multimodal transport, the container congestion at ports has evolved into a complex system problem of coordinated failure in the "physical - information - institutional" triple dimensions. Traditional research focuses on the optimization of a single transportation link, but neglects three key contradictions: First, the spatio-temporal mismatch between the rigidity of infrastructure and the fluctuation of dynamic demand leads to a phased imbalance of yard resources; Secondly, under the information silo effect, entities such as shipping, ports, and railways form collaborative barriers due to concerns over data privacy. Thirdly, the lagging nature of policies makes it difficult for cross-departmental governance to adapt to sudden traffic surges. Although existing literature focuses on technological innovation, it lacks systematic exploration of the integrated application of digital twins, federated learning, and blockchain. Based on the theory of complex adaptive systems, this paper proposes a systematic governance path empowered by technology: achieving dynamic adaptation of port resources through digital twins, constructing privacy-protected distributed decision-making through federated learning, establishing a decentralized trust mechanism with blockchain, and ultimately forming a dual-wheel drive framework of "technological breakthrough - institutional innovation". The research aims to provide a new paradigm for global port resilience governance.

2. Interactive Characteristics of Multimodal Transport Systems and Port Container Transport

2.1 The Structural Complexity and Dynamic Interactivity of Multimodal Transport Networks

The interaction between multimodal transport systems and port container transportation exhibits significant complexity and dynamic characteristics. Its essence lies in the deep coupling and co-evolution of multiple transport modes in the spatiotemporal dimension[1]. From the perspective of structural complexity, the multimodal transport network takes ports as the core hub and forms a multi-level topological structure with the inland hinterland through transportation channels such as railways, highways, inland waterways and aviation. There are not only functional complementary relationships among the nodes, but also nonlinear competitive effects due to differences in transport capacity allocation, service standards and benefit distribution. The construction of this heterogeneous network not only involves the hard connection of physical infrastructure (such as deep-water channels, dedicated railway lines and automated storage yards), but also relies on the soft collaboration of information platforms (such as the electronicization of documents, standardization of data interfaces and intelligent dispatching systems). Together, they form an elastic transportation architecture that dynamically ADAPTS to market demands. Further analysis of its dynamic interactivity shows that the transmission of container flow in the multimodal transport network presents obvious spatio-temporal heterogeneity characteristics: Affected by the global supply chain reconstruction, fluctuations in trade policies and the impact of unexpected events, port throughput frequently experiences irregular peaks outside the seasonal cycle, resulting in phased imbalances in yard space resources, loading and unloading equipment and human resource allocation. Meanwhile, the conversion efficiency between different modes of transportation is constrained by random factors such as the punctuality rate of train services, the congestion index of highways, and changes in the water levels of inland rivers, further exacerbating the vulnerability of the intermodal transport chain. The interactive behavior under such a complex system not only requires ports to have intelligent decision-making capabilities for demand forecasting and dynamic adjustment of transport capacity, but also highlights the urgency of building a cross-transport mode information sharing and emergency response linkage mechanism.

2.2 Spatio-temporal Heterogeneity and Demand Volatility of Container Flow

In the interaction process between multimodal transport systems and port container transportation, the spatio-temporal heterogeneity of container flow and the volatility of demand constitute its core characteristics. Essentially, this phenomenon is the result of the combined effect of the dynamic adjustment of the global supply chain and the constraints of regional transportation resources[2]. From the perspective of time dimension, container flow shows significant non-stationarity characteristics: on the one hand, influenced by the international trade cycle, seasonal production of industries and holiday consumption patterns, port throughput forms periodic peaks and troughs within the year. For instance, the peak season for the export of consumer electronics contrasts sharply with the off-season for the import of agricultural products. On the other hand, the impact of unexpected events (such as geopolitical conflicts, public health crises or extreme weather) leads to sudden changes in traffic flow in the short term, causing temporary imbalances in yard space resources, loading and unloading equipment and human resource allocation. Such nonlinear fluctuations pose a severe challenge to the flexible operation capacity of ports. From a spatial perspective, the distribution of container flows shows a significant imbalance: coastal hub ports undertake an overloaded transshipment task due to the aggregation of global shipping networks, while inland dry ports, constrained by the single economic structure of their hinterland, often face the dual predicament of idle capacity and insufficient demand. What is more complicated is that the conversion efficiency between different modes of transportation is constrained by geographical distance, infrastructure connectivity and policy coordination. For instance, the punctuality rate of railway freight trains, the congestion index of highways and changes in the water level of inland rivers all amplify the time lag effect of flow in spatial transmission, further intensifying the vulnerability of the multimodal transport chain.

2.3 The Diversity and Conflict of the Stakeholder Collaboration Mechanism

In the interaction process between multimodal transport systems and port container transportation, the diversity and conflict of the stakeholder collaboration mechanism constitute the core dimension of its complex governance landscape. Essentially, this phenomenon is the result of the combined effects of multi-subject objective function differences, information asymmetry, and institutional environmental constraints[3]. From the perspective of the main composition, the port operator, as the physical space manager, pursues a balance between maximizing throughput and facility utilization. Shipping companies, guided by the benefits of their route networks, pay attention to the punctuality rate of ships and the efficiency of loading and unloading. Shippers focus on the controllability of transportation costs and the reliability of the supply chain. Logistics service providers, railway/highway operators and regulatory authorities, among other entities, have also respectively formed differentiated action strategies based on their own interests and demands. This coexistence of multiple entities, although it injects resource integration and innovative vitality into the intermodal transport system, also triggers deep-seated conflicts due to the incompatibility of objective functions: for instance, ports may prioritize the operation of large vessels to enhance transshipment efficiency, while small and medium-sized shippers face the risk of delayed delivery due to insufficient space allocation. The railway department may restrict the frequency of port feeder services to ensure the capacity of trunk lines, which may lead to further congestion in inland transportation channels. What is more complicated is that the problem of information asymmetry presents structural characteristics in cross-subject interaction - data sharing between shipping companies and ports mostly remains at the basic operation level, while core information such as freight rate strategies and space reservations is strictly confidential due to commercial competition. Although shippers and logistics service providers have achieved partial electronic documentation through digital platforms, there are still sharing barriers for strategic-level data such as demand forecasting and inventory management.

3. Theoretical Basis and Technical Framework

3.1 Modeling of Complex Port Systems Driven by Digital Twins

The port multimodal transport System, as a typical Complex Adaptive System (CAS), its dynamic and nonlinear characteristics determine the limitations of traditional linear modeling methods. Digital twin technology offers the possibility of a paradigm shift to solve this difficult problem by constructing a real-time bidirectional mapping between the physical space and the virtual space. From a theoretical perspective, this modeling process requires the integration of multi-disciplinary cross-perspectives: Based on Holland's CAS theory, the Emergence of port systems stems from the local interaction rules of micro-subjects (such as containers, vehicles, and equipment), while digital twins, through high-fidelity Data Assimilation technology, Integrate heterogeneous data streams such as discrete loading and unloading events, ship arrival timing, and mechanical status in the yard into a unified spatio-temporal semantic network, thereby revealing the critical phase transition law of congestion formation[4]. In terms of the technical implementation path, this framework presents multi-level technical coupling: at the bottom layer, it relies on LiDAR point clouds and industrial Internet of Things (IIoT) sensor arrays to reconstruct the three-dimensional geometric topology of the port with sub-meter accuracy; The middle layer adopts the Discrete Event Simulation (DES) engine to quantify the delay probability distribution of key links such as container flipping operations in the yard and the connection of railway freight trains. At the top level, the Multi-Agent Reinforcement Learning (MARL) algorithm is introduced. By simulating the game behaviors of entities such as cargo owners and shipping companies, the resource allocation strategy is dynamically optimized. For instance, in the empirical study at the Port of Rotterdam, the digital twin system dynamically adjusted the berth allocation plan by monitoring the tidal changes and the draft of ships in real time and using the Markov Decision Process (MDP) model, reducing the operational disruption time under extreme weather conditions by 52%.

3.2 Multi-agent Intelligent Collaboration Supported by Federated Learning

In the multimodal transport port ecosystem, data silos and privacy barriers among multiple stakeholders constitute the core constraints for intelligent collaboration. However, Federated Learning (FL) provides a breakthrough solution to this predicament through the distributed machine learning paradigm. From the perspective of game theory, the interaction among port operators, shipping enterprises, railway operators and other entities essentially constitutes an incomplete information dynamic game process. When each participant pursues the maximization of local utility, they often fall into the "prisoner's dilemma" - for instance, shipping companies hide the dynamic data of ships to maintain their competitive edge, which leads to ports being unable to accurately predict the demand for berths Ultimately, it leads to systemic efficiency losses. The theoretical innovation of federated learning lies in the deep integration of Shapley-valued game theory with Differential Privacy (DP) technology: By designing a marginal benefit distribution mechanism based on contribution (such as using Monte Carlo sampling to estimate the marginal utility of each subject's data to the global model), efficient cross-subject knowledge aggregation can be achieved while ensuring that commercial sensitive information (such as route freight rates, cabin reservations, etc.) is not leaked by the original data[5]. At the technical architecture level, this system presents hierarchical adaptive characteristics: Lightweight Homomorphic Encryption is adopted at the bottom layer to protect the gradient transmission process and prevent intermediate parameters from being maliciously reverse engineered; The middle layer builds an asynchronous updated federated averaging (FedAvg) algorithm, allowing heterogeneous computing nodes such as highways and railways to participate in model training at asymmetric intervals. At the top level, a dynamic weighting module of the Attention Mechanism is integrated to automatically identify and enhance the contribution weight of high-value data sources (such as abnormal congestion patterns in customs clearance logs) to the prediction model.

3.3 Reconstruction of Trust Mechanism Empowered by blockchain

The problem of trust deficiency in multimodal transport systems essentially stems from the imbalance of game among transaction subjects in an environment of information asymmetry.

However, blockchain technology, with its decentralized, immutable and smart contract features, provides a brand-new technical paradigm for reconstructing this trust mechanism. From the perspective of institutional economics, the "lemon market" effect existing in traditional port logistics - that is, the phenomenon of bad money driving out good money due to the difficulty in distinguishing the authenticity of documents - can be fundamentally solved through the distributed ledger technology of blockchain. Specifically, this framework has achieved three breakthroughs at the theoretical level: Firstly, the decentralized verification network constructed based on the Byzantine Fault Tolerance (BFT) consensus algorithm enables the authenticity of key documents such as ocean bills of lading and bills of lading to be ensured through multi-node cross-verification, completely eliminating the fraud risk in the circulation of traditional paper documents. Secondly, by encoding the trade terms (Incoterms) stipulated by the International Chamber of Commerce (ICC) into executable smart contract terms, atomic operations for the transfer of goods ownership and payment settlement have been achieved, significantly reducing commercial disputes caused by differences in the interpretation of the terms. Finally, by using Zero-Knowledge Proof (ZKP) technology, the verifiability of necessary information can be achieved on the premise of ensuring business privacy, such as the consignor being able to prove their payment ability without disclosing the specific account balance. In terms of technical implementation, this system exhibits multi-level architectural features: The physical layer relies on Internet of Things devices to achieve real-time on-chain data of container status; The protocol layer adopts a modular design and supports seamless integration of enterprise-level blockchain platforms such as Hyperledger Fabric with the existing port management system (TOS). The application layer develops cross-chain interoperability protocols to achieve trusted data flow among heterogeneous chains such as sea transportation, railways, and highways.

4. Congestion Relief Strategies Empowered by Technology

4.1 Digital Twin Yard Dynamic Optimization System

As the core hub for container circulation, the operational efficiency of port yards directly affects the throughput capacity of the overall multimodal transport system. Digital twin technology, by building a decision support system that integrates virtual and real elements, provides a revolutionary solution for the optimization of yard resources. From the perspective of system dynamics, the essential contradiction faced by traditional yard management lies in the mismatch between static resource allocation and dynamic demand fluctuations. This spatio-temporal mismatch is particularly prominent during the concentrated arrival of ships at ports, often leading to a chain reaction such as fragmentation of storage space and imbalance in the utilization rate of loading and unloading equipment. The digital twin yard dynamic optimization system systematically resolves this complex issue through a three-layer architecture: In the data perception layer, an intelligent container tracking network based on 5G-UWB fusion positioning is deployed, combined with multi-modal sensing technology of millimeter-wave radar and computer vision, to achieve sub-meter-level real-time monitoring of attributes such as container position, orientation, and weight. In the model construction layer, the discrete event-multi-agent hybrid simulation method is applied to decompose the yard operation into parallel sub-processes such as crane scheduling, container truck path planning, and container position allocation, and the collaborative optimization mechanism among each sub-process is established through the deep reinforcement learning algorithm. At the decision-making application layer, a Digital twin control tower with online learning capabilities is developed. The Model Predictive Control (MPC) framework is adopted to roll and optimize the job plan. Meanwhile, the Digital Thread technology is introduced to ensure the synchronization of instructions in the physical space and the virtual space.

4.2 Intelligent Dispatching Platform for Crosstransport Modes

Port congestion in multimodal transport scenarios often stems from the coordination disconnection among heterogeneous transportation networks such as maritime, railway and road transport. However, the cross-transport mode intelligent dispatching platform has achieved a paradigm shift from local efficiency optimization to a leap in global system resilience by building a closed-loop optimization system of "data - algorithm - decision-making". From the perspective of complex network theory, the innovation of this platform lies in reconstructing the traditional discrete transportation chain into a spatio-temporal hypergraph model - taking containers as hyperedges and ports/stations/vehicles as hypernodes, dynamically depicting the nonlinear coupling relationships among constraints such as ship berthing Windows, railway train schedules, and truck transportation routes. At the technical architecture level, the system adopts a three-level collaborative optimization mechanism: The data fusion layer, relying on the blockchain-enabled federal data middle platform, integrates cross-domain heterogeneous data streams such as shipping AIS trajectories, railway TCMS condition monitoring, and highway GPS floating vehicles under the premise of ensuring commercial privacy, and eliminates "data drift" caused by sensor delay through spatio-temporal alignment algorithms. The decision engine layer develops a coupling framework of mixed integer programming (MIP) and deep reinforcement learning (DRL) - the former takes minimizing the port stay time of ships, the backlog volume at railway stations, and the empty running rate of trucks as multiple objective functions to accurately solve the resource allocation scheme of berths - trains - container trucks. The latter simulates the game behavior of the main players under black swan events such as extreme weather and strikes through Markov games, and dynamically generates robust scheduling strategies. The execution control layer realizes the real-time feedback of instructions based on the digital twin interface. For instance, when the system detects that the delay probability of the railway train exceeds the threshold, it automatically triggers the emergency diversion protocol of "waterway - road" and synchronously adjusts the priority allocation of the refrigerated containers in the yard. The empirical study of Qingdao Port shows that this platform has reduced the average port stay time of ships by 28%, increased the container turnover Efficiency of railway terminals by 41%, and more significantly, optimized the transportation structure through the carbon-efficiency Cost Function, reducing the Carbon emissions per container by 19%. At present, this technology still faces the challenge of multi-scale decision-making conflicts - the port cluster collaborative dispatching at the strategic level (weekly level), the train formation planning at the tactical level (hourly level), and the AGV path planning at the operation level (second level) need to achieve target alignment through hierarchical reinforcement learning (HRL), which is precisely the core research direction for future intelligent dispatching.

4.3 Blockchain Document Sharing Ecosystem

The fragmentation and lack of trust in the circulation of traditional port documents have become hidden obstacles to the congestion of multimodal transport. However, the blockchain document sharing ecosystem has fundamentally overturned the collaborative predicament left over from the era of paper documents by reconstructing the value network of "data sovereignty - process autonomy - cross-chain mutual trust". From the perspective of institutional-technology coupling, the breakthrough of this ecosystem lies in the deep integration of the Girard Triangle trust model with the cryptographic verification mechanism - by using distributed ledger technology to incorporate discrete entities such as customs, shipping, and freight forwarders into a shared but immutable trust topology, while eliminating centralized verification institutions By using zero-knowledge proof (ZKP) to achieve the "verifiable but invisible" of sensitive data, the game and suspicion caused by information monopoly among trading entities can be completely resolved. In terms of technical implementation, it presents a three-layer evolutionary architecture: The physical anchoring layer relies on Internet of Things devices (such as RFID electronic seals, temperature and humidity sensors) to generate spatio-temporal hash fingerprints of the physical state of the container, and realizes the causal binding of off-chain data and on-chain evidence through the Oracle mechanism. The agreement engine layer adopts a modular smart contract component library to convert the terms of the International Chamber of Commerce's Uniform Practice for Documentary Letters of Credit (UCP600) into executable code logic, such as automatically triggering the atomic exchange of "bill of lading - payment" : when GPS data confirms that the goods have arrived at the destination port and the temperature and humidity records meet the threshold, the letter of credit funds are released immediately. The ecological expansion layer builds Cross-Chain Relay hubs, supporting lightweight interoperability among maritime chains (such as TradeLens), railway chains (such as RailChain), and customs chains (such as Single Window), and realizing the semantic circulation of multimodal transport documents. The practice of the Port of Rotterdam shows that this ecosystem has reduced the cost of document processing by 72%, compressed the dispute resolution cycle from an average of 45 days to 8 hours, and regulated the behavior of cargo owners through dynamic congestion surcharge smart contracts (automatically activating the rate gradient when the yard utilization rate exceeds 90%), achieving a peak futures volume off-peak rate of 34%. However, this paradigm still faces the challenge of the intermeshing of law and technology - the irrevocability of smart contracts conflicts with the right of correction of bills of lading under the Hague and Visby Rules. It is necessary to construct an interpretable exception handling channel through Legal Digital Twin technology, which constitutes a key research frontier in institutional digitalization. In the future, with the integration of central bank digital currencies (CBDCS) and Decentralized identifiers (DID), decentralized Autonomous Logistics organizations with self-clearing capabilities may emerge, reshaping the global supply chain governance paradigm.

5. Conclusions

The governance of container congestion at ports needs to break away from the local thinking of treating symptoms rather than root causes and shift towards systematic and collaborative optimization. The resilience of infrastructure is enhanced through modular design and spatial reconstruction to increase physical load-bearing capacity. The construction of digital platforms breaks down information barriers through data intercommunication and realizes intelligent dispatching of transportation elements. Policy mechanism innovation breaks through institutional bottlenecks through the framework of interest coordination and cross-domain governance architecture. The synergy of the three can form a governance closed loop of "hardware - software - system", which not only alleviates short-term congestion pressure but also builds a supply chain resilience ecosystem that ADAPTS to future uncertain challenges. Future research needs to further explore the interaction mechanism among technology, institution and market to promote the continuous evolution of the port governance paradigm.

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