DIGITAL TWIN-ENABLED COLLABORATIVE GOVERNANCE FOR GREEN SEAPORT–DRY PORT MULTIMODAL CORRIDORS: A MARITIME SILK ROAD PERSPECTIVE

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Abstract. The seaport-dry port multimodal logistics corridors have become significant tools for enhancing connectivity in the hinterland, improving transport efficiency, and promoting a low-carbon transition under the Maritime Silk Road. However, large gateway ports, railway terminals, inland dry ports, trucking operators, shipping companies, customs-related service providers, and logistics customers often operate through fragmented information systems and separate decision-making routines. This fragmentation weakens real-time visibility, rail-interface coordination, green performance monitoring, and risk response across the whole corridor. Taking Ningbo-Zhoushan Port and its hinterland sea-rail intermodal network as an illustrative public-data-based case, this paper develops a digital twin-enabled collaborative governance framework for green seaport-dry port multimodal logistics corridors. The study adopts a conceptual and case-informed research design by integrating literature on digital twins, smart ports, dry ports, port regionalization, carbon-aware multimodal routing, and risk-based route selection. The proposed framework consists of four layers: physical corridor layer, data and interface layer, digital twin analytics layer, and collaborative governance layer. It links operational visibility, rail-interface coordination, carbon-sensitive modal shift, one-bill/one-box service, risk early warning, and institutional coordination. The paper contributes a governance-oriented digital twin architecture and a practical indicator set for Maritime Silk Road logistics corridors.

Keywords: *Digital Twin; Collaborative Governance; Seaport-Dry Port Corridor; Multimodal Transport; Green Logistics; Ningbo-Zhoushan Port; Maritime Silk Road.*

Introduction

The Maritime Silk Road is not only a maritime transport route, but also a port-hinterland logistics system in which seaports, dry ports, railway terminals, road drayage services, customs-related procedures, shipping companies, and logistics platforms jointly determine corridor performance. In this system, a seaport is no longer limited to waterside cargo handling. It increasingly functions as a regional and international logistics organizer that extends services into inland nodes through rail-sea intermodal transport, dry-port cooperation, and digital information platforms. The dry port concept emphasizes the direct connection between seaports and inland intermodal terminals, where containers can be processed in a way similar to seaport operations [5]. Port regionalization also shows that modern port competitiveness depends on the integration of port functions with inland distribution networks and hinterland logistics governance [6].

At the same time, the green transformation of multimodal transport has become a central requirement for corridor development. A well-organized rail-sea intermodal transport can help decrease road congestion, enhance the reliability of the transport flows for containers, and facilitate the transition towards other low-carbon transport modes. But this capability requires a coordinated infrastructure, information systems, business rules, and a governance structure. In reality, many corridors still suffer from a lack of integration between port systems and railway systems, a lack of visibility once containers have entered inland terminals, varied digital expertise of companies in the logistics chain, and a lack of carbon indicators in the daily decision-making process of dispatching.

Digital twin technology can help to solve these problems. A digital twin is a virtual representation of a physical system that is linked to it via data flows, analysis, simulation, and decision support that are continuous in nature [1]. Digitalization, smart-port systems, port community platforms, and the use of IoT devices for monitoring have already enhanced the visibility of port operations and the efficiency of services in port and logistics contexts [2,3,4]. Nevertheless, most existing applications remain concentrated within single ports, terminals, or logistics facilities. Less attention has been paid to how digital twin technology can support collaborative governance across a whole seaport-dry port multimodal corridor.

Ningbo-Zhoushan Port provides an appropriate illustrative case for this research. Publicly searchable information shows that the port has developed into a world-level gateway port with strong container handling capacity, extensive sea-rail intermodal services, inland dry-port cooperation, digital port services, and a green port policy orientation. These characteristics make it suitable for examining how a digital twin-enabled governance framework can be designed for a green seaport-dry port corridor under the Maritime Silk Road perspective.

The objective of this paper is therefore to answer the following research question: how can a digital twin-enabled collaborative governance framework be constructed to improve the efficiency, visibility, resilience, and green performance of seaport-dry port multimodal logistics corridors? To answer this question, the paper develops a four-layer framework and an indicator system that can be applied to corridors such as Ningbo-Zhoushan Port-inland dry port networks and, by extension, China-Central Asia logistics connections.

Literature Review

Digital twin research has developed rapidly in manufacturing, logistics, transportation, and infrastructure management. Tao et al. define the digital twin as an enabling technology that integrates physical entities, virtual models, data connections, and service systems [1]. The real essence of this idea is not just visualization, but constant interaction between the physical system and the virtual model. In this way, the operator can keep an eye on the situation in real-time, simulate future scenarios, find potential bottlenecks, and make predictions for decision-making.

Digital transformation is a significant driver for improving port productivity and sustainability in maritime logistics. Heilig et al. claim that digitalization broadens the management scope of maritime ports and opens the door to improved coordination and cooperation among various stakeholders, but that the economic and governance aspects are also crucial [2]. Molavi et al. suggest a smart port framework and a smart port index, emphasizing operational efficiency, safety, security, environmental performance, and resilience [3]. In addition, Kapkaeva et al. demonstrate how port community systems and digital information exchange can link the port authorities, terminal operators, customs-related actors, transport providers, and customers through port digital platforms [4]. These studies point out the potential benefits of digital technologies to port operations, though multi-actor coordination is required.

The spatial and institutional foundations of seaport-dry port corridor research are dry ports and port regionalization. According to Roso et al., a dry port is an intermodal terminal that lies inland and is directly connected to a seaport via railway, and the dry-port concept can help to change the mode of transport from road to more energy-efficient modes, as well as alleviate congestion around the cities of ports [5]. Notteboom and Rodrigue present the port regionalization concept, which demonstrates that port development is no longer limited to the traditional port area and requires inland logistics integration [6]. These theories propose thinking of a contemporary port corridor as a governance network and not a transport chain.

Another important foundation is provided by green multimodal transport studies. Laurent et al. build the CarbonRoadMap as a multi-criteria decision-making tool for transport planning that takes into account the transport costs, delay, and carbon emissions of multimodal transport solutions [7]. In multimodal transportation networks, transport route decisions are often trade-offs among cost, time, and risk, as demonstrated by Koohathongsumrit and Meethom using a fuzzy risk assessment and data envelopment analysis approach for route selection [8]. Yang et al. construct a highway-railway multimodal path optimization model considering carbon emissions, and show that multimodal routing can be evaluated from both efficiency and carbon-emission aspects [9]. Zhao et al. explore sustainable and smart port development and demonstrate that smart technologies can contribute to the integration of economic, environmental, and social aspects in ports [10]. Belmoukari et al. also show, by a systematic literature review, that smart ports are more and more related to digitalization, sustainability, and Industry 4.0 practices [11].

While these studies provide good theoretical support, there are three research gaps. One is that digital twin studies tend to be centered on technology architectures, and less is written about the issues of governance in the corridors. Second, smart port and dry port studies often examine port or terminal systems separately, while the interface between seaports, railways, dry ports, trucking, and customer service remains fragmented. Third, green multimodal studies provide optimization models, but their indicators are not always embedded in day-to-day collaborative governance. This paper addresses these gaps by proposing a digital twin-enabled collaborative governance framework for green seaport-dry port multimodal corridors.

Research Methodology

This paper adopts a conceptual and case-informed research design. The research is not intended to conduct a confidential enterprise-data analysis or a statistical test. Instead, it develops a governance framework by combining academic literature, publicly searchable port and logistics information, and the practical characteristics of the Ningbo-Zhoushan Port hinterland multimodal network.

The research process consists of four steps. First, the relevant literature on digital twins, smart ports, dry ports, port regionalization, carbon-aware multimodal transport, and risk-based route selection is reviewed. This step identifies the theoretical components that should be included in a corridor-level governance framework. Second, the case background of Ningbo-Zhoushan Port is examined through publicly available and online-searchable information, including port throughput scale, sea-rail intermodal development, dry-port connectivity, digital service practices, and green development orientation. Third, corridor governance problems are mapped from the perspective of data flow, modal interface, service process, carbon monitoring, and risk response. Fourth, a four-layer digital twin governance framework and a practical indicator set are constructed.

The empirical background is treated as illustrative rather than as a confidential dataset. Therefore, the article does not disclose or depend on internal enterprise documents. Ningbo-Zhoushan Port is used as a representative gateway port because its public profile reflects the common characteristics of large Maritime Silk Road logistics corridors: high cargo volume, large container flows, expanding rail-sea intermodal services, dry-port cooperation, digital platform development, and increasing green governance requirements.

Table 1. Research logic and analytical focus

Research element	Main content	Function in this paper
Theoretical basis	Digital twin, smart port, dry port, port regionalization, green multimodal routing	Defines the conceptual foundation of the framework
Case background	Ningbo-Zhoushan Port and its hinterland sea-rail intermodal network	Provides an illustrative Maritime Silk Road corridor context

Research element	Main content	Function in this paper
Governance problem	Fragmented data, interface delay, modal coordination gap, green-performance discontinuity	Identifies why a corridor-level digital twin is needed
Framework design	Physical corridor, data interface, digital twin analytics, collaborative governance	Builds the proposed model
Indicator design	Visibility, rail-interface efficiency, carbon-sensitive modal shift, risk warning, service integration	Translates the framework into practical governance tools

Results and Discussion

Corridor governance problems in seaport-dry port multimodal logistics

A seaport-dry port corridor cannot be equated with a single port or a single freight terminal, as its performance depends on multiple nodes, actors, systems, and rules. Based on public information and industry practice, it can be seen that in the context of the Ningbo-Zhoushan Port hinterland, the port has a very rich sea-rail intermodal service, inland dry port, and digital port service function. But, as networks grow, so do the governance challenges.

The first one is data fragmentation. Data from seaport terminal operating systems, railway freight systems, trucking platforms, dry-port yard systems, customs-related service platforms, and customer service channels can have varying data standards and update frequencies. While individual systems may perform perfectly, the entire corridor might not have a single picture of the location of the container, status of the document, train availability, truck booking, yard congestion, and expected time of arrival.

The second issue is modal-interface delay. Smooth interfaces among ship, terminal, rail, road, and dry-port operations are needed in multimodal transport. Synchronization of container availability by port, allocation of railway wagons, availability of space in inland yards, and scheduling of road drayage can cause containers to wait at the wrong node, unbalance equipment utilization, and cause customer delivery uncertainty.

The third issue is incomplete monitoring of corridor-level green performance. With regard to green logistics, it is not possible to measure just the total volumes in ports or on the railways. These indicators need to include rail-interface share, green drayage share, energy use of yard equipment, carbon-sensitive routing, and empty-container repositioning efficiency, among others, at the corridor level. In the absence of a common data layer, the monitoring of these indicators is not easily done on a continuous basis.

The fourth one is risk response. Interruptions like a ship delay, a railway capacity constraint, an extreme weather event, a customs inspection overload, a truck jam, or a dry-port yard overload can ripple through the corridor. Traditional governance is more likely to react once the problem has been made apparent. An ability to detect earlier and respond based on scenarios should be a feature of a digital twin.

Digital twin-enabled collaborative governance framework

This paper introduces a four-layer collaborative governance framework for solving the above problems based on digital twins. The framework does not aim to replace the enterprise systems which are already in place. Rather, it establishes a virtual governance layer (at the corridor level) which links relevant data, models, indicators, and decision rules among the participating actors.

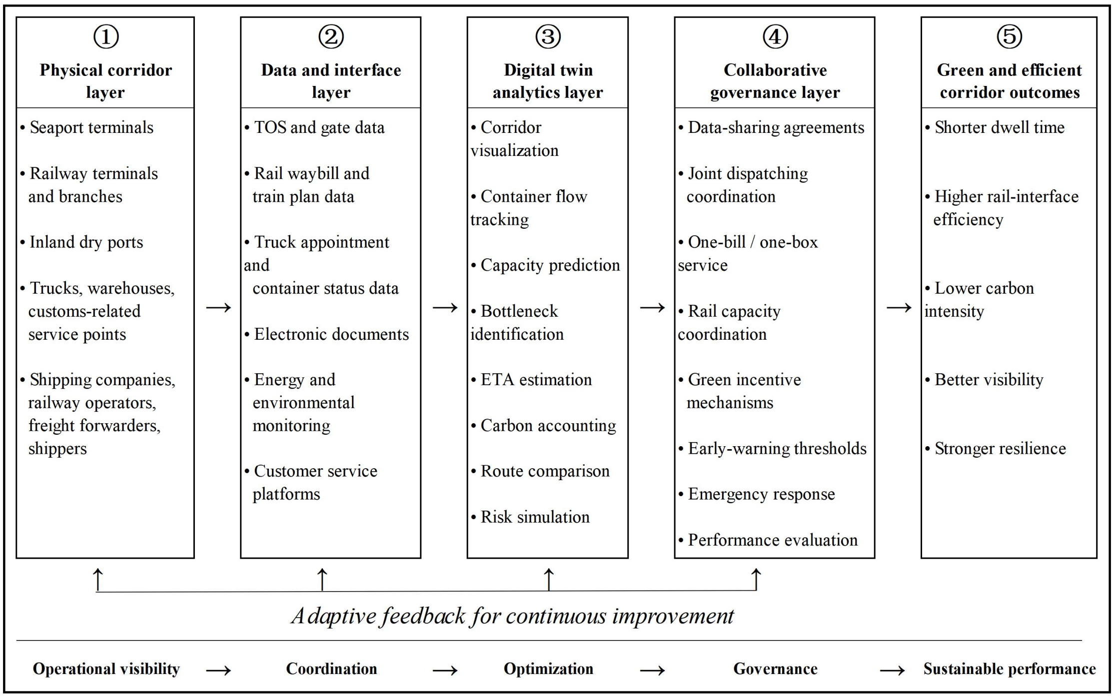

Figure 1. Digital twin-enabled collaborative governance framework

The physical corridor layer comprises seaport terminals, railway branches, inland dry ports, road drayage fleets, warehouses, customs-related service points, shipping companies, railway operators, freight forwarders, and shippers. This is the actual logistics network.

The data and interface layer collects operational data from terminal operating systems, railway bills, truck appointment systems, container status data, gate data, electronic documents, energy monitoring, environmental monitoring, and customer service platforms. It is important, however, that the data exchange and event synchronization are standardized, not just data collection.

The digital twin analytics layer converts corridor data into dynamic virtual representations. It has features such as corridor visualization, container flow tracking, capacity prediction, identification of bottlenecks, estimating ETAs, carbon accounting, route comparison, and risk simulation. This layer should be capable of answering practical questions such as: where is the container, which interface is delayed, which dry port is under pressure, which route has lower carbon emissions, and which disruption may affect delivery reliability?

The collaborative governance layer converts analytical results into institutional and operational actions. It includes data sharing agreements, dispatching coordination, one-bill/one-box service rules, rail capacity coordination, green incentive mechanisms, early-warning thresholds, emergency response procedures, and performance evaluation. This layer is essential because technology alone cannot solve corridor fragmentation without governance rules.

Table 2. A four-layer framework for digital twin-enabled corridor governance

Layer	Core components	Main governance function
Physical corridor layer	Seaport terminals, railway terminals, inland dry ports, trucks, warehouses, customs-related service points	Defines the real operational network
Data and interface layer	TOS data, railway bill of lading data, gate data, AIS/ETA data, container status, energy and environmental data, electronic documents	Builds a shared data foundation
Digital twin analytics layer	Visualization, simulation, prediction, optimization, carbon accounting, risk warning	Converts data into decision support
Collaborative governance layer	Data-sharing rules, joint dispatching, one-bill service, green incentives, emergency response, and an evaluation mechanism	Converts analytics into coordinated action

Layer	Core components	Main governance function
Outcome layer	Shorter dwell time, higher rail-interface efficiency, lower carbon intensity, better visibility, stronger resilience	Measures corridor improvement

Application logic for the Ningbo-Zhoushan Port corridor

For Ningbo-Zhoushan Port, the proposed framework can be applied through a corridor mirror rather than a single terminal model. The digital twin should begin with the high-frequency container flow between the seaport and inland dry ports. The first task is to build a container event chain. Key events to be included in each container should include arrival at the port, discharge, customs-related release, yard location, rail plan confirmation, gate movement, train loading, train departure, inland arrival, dry-port unloading, and final delivery. These events, when linked, can translate node-by-node tracking in the corridor to whole process visibility.

The second one is constructing an interface coordination model. The most critical interface is the one between port yard operations and railway departure planning. A digital twin can be used to compare port-side container readiness with available rail capacity, the train timetable, inland yard capacity, and truck appointment demand. When the rail plan is inadequate, the system can detect the prospect of rail backlog before it turns into a yard congestion issue. The system can adjust railway loading priority or alert inland actors in advance if port-side container release is delayed.

The third is to make green performance a part of dispatching. General policy statements are not all that are needed for a green corridor. It needs to be measured and have indicators. For instance, rail share can reveal if there's a greater amount of containers moving from road to rail. Carbon-sensitive routing can consider various routing options based on time, cost, risk, and emissions. Energy Monitoring can reveal if terminal and yard equipment are making progress towards clean energy. These indicators can be visualised for port managers, railway operators, dry-port managers, and policy actors using digital twin analytics.

The fourth one is to facilitate logistics connectivity between China and Central Asian countries. From the Maritime Silk Road point of view, Ningbo-Zhoushan Port could be a maritime gateway, and the dry port in inland areas as well as the logistics nodes in Central Asia could be extended hinterland platforms. A corridor digital twin can be used to align maritime schedules, rail departures, inland terminal capacity, and customer delivery requirements. In the case of landlocked markets, the importance of the corridor is not just its size but also the quality and reliability of its inland connectivity, as well as transparent logistics services.

Corridor indicator system and early-warning mechanism

Practical indicators should be incorporated in a digital twin-enabled governance framework and should be updated regularly. Such indicators must include aspects of operational efficiency, service integration, green performance, and risk warning. Table 3 suggests a set of indicators for a green seaport-dry port multimodal logistics corridor.

Table 3. Proposed indicators for green seaport-dry port corridor governance

Dimension	Indicator	Formula or measurement logic	Governance meaning
Plan execution	Completion ratio		Compares actual corridor performance with planned target
Rail interface	Rail-interface share		Measures the role of rail-sea intermodal transport
Interface balance	Interface gap		Identifies whether rail performance lags behind overall port growth
Visibility	Tracking coverage		Measures whole-process container visibility
Data quality	Data latency		Identifies delayed information feedback
Service integration	One-bill coverage		Measures the maturity of integrated intermodal service

Dimension	Indicator	Formula or measurement logic	Governance meaning
Efficiency	Average container dwell time		Measures port/rail interface waiting time
Green performance	Carbon-sensitive modal index		Estimates corridor carbon intensity by mode
Risk warning	Disruption warning score	Weighted score of delay, congestion, capacity shortage, weather, and document risk	Supports early response before disruption spreads

A simple 3-color logic can be used for the early-warning mechanism. A green signal indicates that the indicator is attaining a planned benchmark and does not have any significant deterioration. The yellow signal indicates that the benchmark is not being achieved or the trend is not getting stronger. A red signal indicates that pressure is indicated from both the benchmark and the trend. This logic is very convenient for management communication, since it can be turned into signals that are easy to act on within the corridor.

For instance, if the total container throughput increases rapidly, while the share of containers on the rail interface does not increase proportionately, the interface gap will be widening. The digital twin should then alert port and railway actors to review rail capacity, loading priority, inland terminal capacity, or customer incentives. The system may seem complete with a high tracking coverage, yet fail to get real-time decisions due to long data latency. If the level of one-bill coverage is not high, then customers will have to deal with more than one document and platform, which defeats the purpose of multimodal service integration.

Governance implications

The proposed framework has three governance implications: Firstly, the development of the digital twin should begin with problems in the corridors and not with the presentation of the technology. A visually attractive platform is not enough. The system should address practical problems like container tracking, scheduling with rail interfaces, document coordination, carbon accounting, and disruption warning.

Second, digital twin governance requires data-sharing rules. Ports, railway operators, dry ports, trucking companies, shipping companies, and customers have different interests. Some data may be commercially sensitive. Hence, it is necessary that the corridor platform implement the following: graded data sharing, standard interfaces, data security mechanisms, and clear responsibility allocation. The governance question is not whether all data should be opened, but which data should be shared at what granularity, with whom, and for what operational purpose.

Third, green corridor development requires linking incentives with measurable indicators. If rail-interface share, green drayage share, carbon intensity, and dwell time can be monitored, policy support and enterprise incentives can become more precise. This can help avoid a situation in which green logistics remains a slogan rather than an operational management mechanism.

Conclusion

This paper developed a digital twin-enabled collaborative governance framework for green seaport-dry port multimodal logistics corridors under the Maritime Silk Road perspective. Taking Ningbo-Zhoushan Port and its hinterland sea-rail intermodal network as an illustrative public-data-based case, the paper argued that corridor performance depends on more than port throughput or terminal automation. It requires whole-process visibility, rail-interface coordination, green-performance monitoring, risk early warning, and multi-actor governance.

The proposed framework includes four layers: the physical corridor layer, the data and interface layer, the digital twin analytics layer, and the collaborative governance layer. It connects operational data, virtual corridor modeling, carbon-sensitive analysis, service integration, and institutional coordination. The proposed indicator system further translates the framework into measurable tools, including completion ratio, rail-interface share, interface gap, tracking coverage, data latency, one-bill coverage, dwell time, carbon-sensitive modal index, and disruption warning score.

The contribution of this paper is to shift the discussion of digital twin technology from a single-port or single-terminal tool to a corridor-level governance mechanism. This is particularly relevant for Maritime Silk Road logistics corridors, where seaports, dry ports, railway networks, and inland markets must operate as an integrated system. The framework can be tested in the future by further elaborating the operational data, by providing simulation models, and by comparing it with other seaport-dry port corridors.

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