

REVIEW ARTICLE

Analysis of Risk Characteristics in Digital Port Operations and Governance Pathways

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ABSTRACT

Digital transformation represents a pivotal trend in global economic integration. As a critical node in the modern logistics system, digital ports exhibit increasingly prominent operational risk characteristics spanning information security, cybersecurity, and supply chain management. These risks may lead to cargo loss, data breaches, and system failures, severely disrupting port operations and damaging corporate reputation. This study systematically examines the risk characteristics of digital port operations and proposes effective governance pathways. Under the digital economy, port operational risks demonstrate new features of complexity, interactivity, and synergy. This research classifies the operational risks of port enterprises into five categories: strategic, financial, market, operational, and legal risks, analyzing them from both macro (policies, economic environment, technological development) and micro (internal management, partnerships, market competition) perspectives. The study further identifies the leading role of competent government authorities in port risk supervision and proposes four governance pathways: establishing an integrated risk-control and compliance management system, strengthening accounts receivable risk prevention through digital management, enhancing cargo management through digital virtual-real coordination, and building blockchain-based risk governance capabilities. The findings provide valuable insights for constructing world-class ports and advancing China's transportation power.

Keywords: Digital port; Operation and governance; Risk characteristics; Audit governance

INTRODUCTION

Ports serve as barometers of the national economy and vital links in international trade. The management of port operational risks has a long history and is deeply embedded in port enterprises. Existing literature falls into three categories: (1) financial risk management with financial audit as the main axis, focusing on reducing accounts receivable stock, shortening collection cycles, and optimizing capital flow^[1,2]; (2) internal audit supervision emphasizing standardization across financial management, operational business, market sales, and internal control^[3,4]; (3) collaborative risk management aligning national and local regulations with enterprise strategy and development stages^[5,6].

Since the new era, information technology and management innovation have driven port upgrading and improved operational governance capacity. The 20th National Congress established the digital economy as a national strategy. Port digital construction has undergone a profound transformation from information technology to automation and intelligence, driving fundamental changes in operational and management modes. Consequently, port operational risks exhibit new characteristics of complexity, systematization, and coordination. Academician Yan Xiping proposed smart port development driven by virtual-real integration, aiming to leverage the achievements of the technological revolution for port application and management innovation^[7].

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Received: 8 March 2025; Revised: 12 March 2025; Accepted: 7 July 2025

<https://doi.org/10.67229/stemer.26080011>

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This study investigates major coastal ports—Qingdao, Rizhao, Yantai, Shanghai, Tianjin, Ningbo, Xiamen, Shenzhen, and Guangzhou—covering the period from 2018 to 2023. Research methods include literature review, policy interpretation, network analysis, questionnaires, and field interviews. The processed and analyzed data form the basis of the findings presented herein.

THE EVOLUTION AND RISK CHARACTERISTICS OF DIGITAL PORT CONSTRUCTION

Cognitive Evolution of Digital Ports

The conceptual foundation and policy support for digital port construction have deep historical roots^[8,9]. During the 9th Five-Year Plan period, the state proposed building large ports and gradually introduced supportive policies. The 10th and 11th Five-Year Plans emphasized strengthening port construction, expanding throughput, and establishing a modern transportation system. The 12th and 13th Five-Year Plans clarified goals for scale expansion and modernization while promoting digital and intelligent development. Since 2017, a series of key policies has supported the transformation towards smart ports, with demonstration ports achieving breakthroughs in automated operations, land-transport coordination, information sharing, and logistics chain innovation.

In 2019, the Guiding Opinions on Building World-Class Ports established specific requirements across development goals, policy measures, and safeguard mechanisms. The 14th Five-Year Plan Outline and 2035 Long-Term Objectives strategically positioned digital China and the digital economy, explicitly calling for accelerated digital port construction. General Secretary Xi Jinping's inspections of Tianjin, Shanghai, Qingdao, and Wuhan ports emphasized the adoption of new technologies, accelerated automation upgrades, and strengthened risk prevention—positioning ports as engines of regional and international economic development.

Port digitization entails the digital transformation of all business processes through technological applications that enhance production efficiency and service quality. Digital ports represent an upgrade from traditional operations to technology-enabled management, operations, and services. Advanced technologies—including IoT, cloud computing, big data, artificial intelligence, and digital twins—enable visual management, data sharing, and automated control. Digital twin technology, in particular, serves as a critical technical foundation for achieving high-quality, sustainable development.

Risk Characteristics of Digital Port Operation

The Fourth Industrial Revolution—characterized by cloud computing, digitalization, networking, and intelli-

gence—has driven profound societal changes. Digital ports are defined by twenty interconnected elements, as systematically catalogued in Table 1.

Table 1: List of Characteristic Analysis of Digital Ports

No.	Feature	Characterization
1	Technical innovation	Adopts cloud computing, big data, IoT to drive technological upgrading of the port industry.
2	Intelligentization	Integrates intelligent control systems for automated operations and smart management, improving efficiency and safety.
3	Data-driven	Optimizes resource allocation, transport organization, and decision-making through data collection and analysis.
4	Intelligent logistics	Deeply integrates logistics, information flow, and capital flow for end-to-end intelligent logistics.
5	Visual management	Enables real-time monitoring of all operational links through visualization technology.
6	System integration	Achieves efficient collaboration and information exchange across all port management systems.
7	Green & sustainable	Prioritizes clean energy, emission reduction, and green port construction.
8	Security	Strengthens information and logistics security through technical safeguards.
9	Innovation cooperation	Promotes collaboration between port enterprises, research institutions, and technology companies.
10	Data sharing	Encourages inter-enterprise data sharing for optimal resource allocation.
11	Multimodal transport	Integrates shipping, highway, and railway modes for combined transport services.
12	Intelligent warehousing	Applies IoT for smart warehouse management and goods distribution.
13	E-Commerce	Develops cross-border trade and digital platform services.
14	Blockchain application	Enhances cargo traceability, contract management, and payment settlement transparency.
15	Artificial intelligence	Enables intelligent prediction, optimized scheduling, and risk assessment.
16	Network security	Protects critical information and data against cyber attacks and leakage.
17	Service experience	Provides convenient, efficient, and personalized port services through technology.
18	Resource integration	Optimizes resource utilization for economic and environmental adaptability.
19	International cooperation	Promotes standardization and mutual recognition to enhance global competitiveness.

Connotation and Characteristics of Digital Port Operation Risks

Risk Connotation

Five principal risk domains define digital port operations. Information security risks arise from massive data dependencies and sensitive information exposure, potentially causing data leakage and cyber attacks. Technical risks stem from the varying maturity levels of IoT, AI, and other high-tech applications, demanding substantial technical capacity. Personnel risks reflect fierce competition for data analysts and cybersecurity specialists. Management risks emerge from the need to develop compre-

hensive systems spanning data governance, information security, technology management, and talent management. Policy risks persist because digital ports remain an emerging concept with evolving regulatory frameworks.

Risk Characteristics

Digital port operational risks permeate the entire production process, exhibiting interactivity, complexity, and cooperativity. These risks are interactive—a failure in one subsystem can cascade across interconnected digital platforms. They are complex, arising from the convergence of multiple technologies, stakeholders, and operational domains. They are cooperative, requiring coordinated governance across enterprise, industry, and regulatory boundaries. The five risk categories—information security, technical, personnel, management, and policy—are not isolated but form an interdependent web that demands systemic governance approaches.

ANALYSIS OF THE MAIN RISKS FACED BY PORT ENTERPRISES

From the perspective of digital port development, aligned with China's current port laws and governance standards, operational risks are systematically classified into five categories: strategic, financial, market, operational, and legal risks.

Strategic Construction Risks

Strategic Risks of Diversified Operations

Diversification transforms traditional loading/unloading and warehousing businesses into integrated supply chain service providers. However, this strategy introduces multiple risk dimensions. Unclear strategic positioning leads to directionless resource allocation. Resource diversion from original core businesses may weaken established competitive advantages. Overall market risk means that systemic shocks can negate diversification benefits. Industry entry barriers—strict regulations, R&D intensity, environmental requirements, and capital demands—increase costs and risks for new ventures. Market conditions including size, growth rate, and competitive intensity determine risk exposure; entering saturated markets with undifferentiated offerings jeopardizes profitability.

Shandong Port exemplifies strategic success: implementing the national blue economy and marine transportation strategy and provincial three-year action plan, it coordinates traditional and emerging businesses across four port groups and twelve business segments, achieving differentiated, synergistic development.

Outbound Investment Risks

In the era of large ports, domestic and international investment activities have become increasingly common and extensive. Insufficient risk assessment, inadequate

process supervision, and weak post-investment evaluation lead to inefficient, high-risk investments. Natural risks include earthquakes, storms, and harsh site conditions. Social risks encompass local customs, cultural differences, and social stability concerns. Governmental risks involve political instability and ethnic disputes. Policy and regulatory risks arise from imperfect or changing legal frameworks. Market risks include demand fluctuations, price volatility, and competitive dynamics.

Financial Management Risks

Accounts Receivable Risk

Accounts receivable risk encompasses collection risk and bad debt risk. High receivable ratios indicate significant credit risk. The post-paid service model prevalent in global port operations delays cash recovery, inflates receivable scale, and extends collection cycles. Moreover, enterprises often lose physical control of goods while receivables remain outstanding, and these claims lack liquidity—they cannot be readily mortgaged or sold for immediate realization.

Profitability Uncertainty

Multiple external and internal factors create profitability uncertainty. Declining operating revenue growth results from supply-demand restructuring, shrinking shipping demand, and intensified competition. Rising costs—labor, materials, and port charges—combined with lagging revenue growth compress margins. Poor cash flow from aggressive expansion increases debt pressure. Industrial policy shifts can erode competitive advantages. Additionally, maritime accidents and ship collisions introduce unexpected adverse effects on operations.

Market Operation Risks

Macroeconomic Risks

Domestic and international macroeconomic fluctuations pose multi-dimensional risks. Domestically, China's economic growth moderation and trade tensions create a challenging external environment; the COVID-19 pandemic in 2020 dramatically reduced cargo and container throughput nationwide. Internationally, sluggish global growth and trade tensions affect import-export operations. China's supply-side structural reform and shift toward high-quality development imply slowing port business growth and intensifying operational pressure.

Policy Adjustment Risks

Policy adjustments create two risk streams: legal risks from regulatory change and operational risks from policy shifts. Changes in market access, taxation, land use, and environmental requirements alter the competitive landscape. Adjustments to subsidy policies and tax regimes affect investment decisions and capital flows. Tariff policy changes impact import/export costs. Labor law and environmental policy revisions modify contractual

obligations and compliance requirements.

Hinterland Economy Dependency

Port hinterlands provide the foundational cargo base. Economic fluctuations directly reduce trade volumes and logistics demand. Regional competition drives harmful price wars among similar ports. Evolving customer needs require continuous service innovation. Policy changes in taxation, land use, and environmental regulation within hinterland economies create cascading effects on port viability.

Operation and Management Risks

Safety Risks

Safety risks represent the most direct and severe threat. Equipment failures, improper operations, habitual violations, and inadequate skills cause cargo damage and injuries. Environmental risks—waves, tsunamis, storms, currents, and tides—disrupt navigation and handling operations. Dangerous goods container management involves control lapses, insufficient safety investment, illegal operations, and equipment failures. Transportation risks arise from interacting vehicle flows, dangerous goods leakage, and substandard traffic planning. Lifting equipment such as tower cranes and gantry cranes introduces additional hazards.

Data Security and Information Confidentiality

Under the digital economy paradigm, data is the core asset of port operations. Data breach risks involve unauthorized exposure of customer information, cargo details, and contract terms—potentially damaging reputation and threatening national security. Data tampering risks during transmission and storage can mislead decision-making. Data security events—hacker attacks, virus outbreaks, and ransomware—increase with digital reliance. Regulatory compliance risks under data protection laws create potential legal sanctions.

Environmental Protection Risks

Port environmental risks are multi-source (self-generated and externally imported pollution), complex (spanning EIA, planning, and project assessment), uncertain (affected by unpredictable external events), and spatiotemporal (varying with seasons and climate). Pollution sources include noise, air emissions, water contamination, ship discharges, container storage, and channel dredging.

Occupational Health Risks

Port work environments expose employees to physical harm (noise-induced hearing loss, vibration injuries, musculoskeletal disorders), chemical hazards (cleaners, paints, lubricants causing skin and respiratory issues), extreme weather conditions, and psychosocial stressors from high-pressure, long-hour work schedules.

Cargo Management Risks

Cargo rights disputes arise from improper issuance of deposit certificates and manifest documents without owner consent, as well as irregular handover and release procedures. Storage quality risks include moisture damage, mildew, consumption losses, and inventory discrepancies. Regulatory release risks involve unauthorized container movements and procedural lapses in customs-supervised cargo handling.

Project Construction Risks

Port engineering risks are complex in origin (natural disasters, technical, market, economic, and political), difficult to assess (requiring hierarchical analysis, causal mapping, event trees), poorly diversified (often unpredictable and uncontrollable), and wide-ranging in impact—affecting surrounding environments, communities, and the entire port industry. Inadequate research, unrealistic scheduling, and procedural deficiencies cause delays, acceptance failures, and asset idling.

Legal Potential Risks

Institutional Compliance Risks

Compliance failures include delayed conveyance of regulatory requirements, omissions in implementing port operation guidelines, inadequate understanding of export control regulations, and safety violations in dangerous goods handling^[10]. Ports may fail to fulfill licensing obligations, emergency rescue duties, production safety requirements, and fair competition mandates.

Contract Management Risks

Contract risks stem from informal written agreements, defective contract texts, and insufficient attention to contract administration. Management errors in conclusion, clause review, and modification—including missing essential terms or accepting unreasonable provisions—cause significant enterprise losses.

Guarantee Liability Risks

Guarantee liability manifests as financial risk (contingent liabilities becoming real obligations) and performance risk (guaranteed loans materializing as actual debt). When debtors default, guarantors face joint liability, credit damage, and financial loss—potentially seriously affecting enterprise performance.

LEADING AND TRANSFER INFLUENCE OF RISK SUPERVISION CARRIERS OF COMPETENT AUTHORITIES

Port enterprises form the foundation of the national economy, yet their operational risks are too complex for individual ports to manage alone. Since 2001, China has deepened port management system reform, delegating administration to local governments under the "one

port, one administration" principle. The Ministry of Transport provides national-level leadership, while local port administrative departments exercise jurisdiction within their areas. The risk supervision framework spans four domains: port planning, port construction, port operation, and port security (Table 2).

Table 2: Regulatory Content and Supervision Framework of Competent Authorities

No.	Regulatory content	Supervising subject	Leading & transfer influence
1	Port & Harbor Planning	National & Local Government	National layout plans formulated by the Ministry of Transport with stakeholder consultation; provincial plans compiled per national framework and submitted for comment.
2	Harbor Construction	National Government & Port Enterprises	Approval per state provisions; EIA required; safety/environmental facilities concurrent with main works; penalties for violations include correction orders, demolition, and fines.
3	Port Management	National Government & Port Enterprises	Ports operate independently post-reform; access permits and filing systems; pricing rules (government-set, guided, market-adjusted); fair competition obligations enforced.
4	Port Security	National Government & Port Enterprises	Ports must comply with Production Safety Law and Transport Ministry rules; establish safety responsibility systems; violations trigger penalties including license revocation or criminal liability.

DIGITAL PORT ENTERPRISE OPERATIONAL RISK PREVENTION AND CONTROL MEASURES

Establish an Integrated Large Risk-Control Compliance Management System

A three-function working group—risk management, internal control, and compliance—establishes integration goals across departments. Implementation focuses on five integration dimensions: organizational structure, workflow, tools and methods, reporting, and safeguard systems. The integrated system pursues both "form" (structural completeness) and "spirit" (adaptive functionality), reducing redundant work while maintaining comprehensive coverage.

Digital Compliance Management and Responsibility Allocation

Establish a digital compliance system with policy, training, inspection, and reporting modules. Clarify process ownership with designated responsible persons at each stage—risk assessment, compliance checking, rectification, and tracking. Implement digital compliance training for all employees, linking assessment results to perform-

ance evaluation and promotion. Shandong Port's practice offers a model: a group-level Compliance Committee chaired by the Party Secretary/Chairman, with the General Counsel serving as Office Director. Each unit designates compliance liaison officers, forming a collaborative network. The principle of "business managers responsible for compliance and risk" creates front-line prevention by business departments, mid-process legal/financial oversight, and post-event disciplinary/audit supervision.

Integrating Compliance into Rules and Systems

Develop a "1+1+N" compliance framework: one top-level policy, one basic system, and N specific guidelines. Six specialized compliance guidelines address cargo delivery, bidding and procurement, and agency construction projects. Systematic review and updating of existing regulations ensures full coverage external obligations incorporated into internal systems supporting high-quality port development.

Embedding Compliance into Operational Procedures

Compliance must be woven into the entire operational lifecycle. Full-cycle contract management extends risk prevention from approval to consultation, signing, review, and performance—with legal personnel participating in major negotiations, model texts standardizing key clauses, and online performance tracking via financial platform integration. Full-coverage legal review of major decisions achieves 100% review and pass rates for important rules, economic contracts, and key decisions.

Cultivating Digital Port Compliance Culture

Compliance culture requires systemic embedding through five modules (Table 3): establishing digital compliance systems, strengthening employee training with performance linkage, creating publicity mechanisms (posters, competitions, newsletters), enabling violation reporting channels, and incentivizing compliant behavior through recognition and rewards. Shandong Port exemplifies this through regular legal study sessions for leadership (100+ sessions), annual Compliance Culture Month activities, and organization-wide commitment signing.

Digital Empowerment of Compliance Management

Digital transformation enables multi-party coordination through a digital twin system, enhanced data governance, and intelligent equipment upgrades. A contract management platform with smart seals enables online approval and performance tracking. A legal management platform digitalizes corporate governance records. An upgraded internal control evaluation information system enables comprehensive online sampling and process marking—embedding compliance requirements directly into information systems.

Table 3: Methods and Paths for Promoting Compliance Culture

Module	Content interpretation
Digital compliance system	Establish comprehensive compliance regulations, processes, and standards with automated digital management and supervision.
Staff training	Conduct online learning and simulation exercises; link training outcomes to performance evaluation.
Publicity mechanism	Deploy posters, compliance information pushes, and knowledge competitions to build awareness.
Violation reporting	Enable real-time reporting channels for timely detection and handling of violations.
Incentive mechanism	Reward compliance-active employees with commendations and bonuses to encourage participation.

Strengthen Accounts Receivable Risk Prevention and Control

Key measures include robust credit management, strict customer screening, comprehensive credit records, clear receivables workflows, supply chain supervision, and diversified financing. Financial instruments such as factoring can transfer receivable risk and improve capital efficiency.

Scientific Credit Rating Evaluation

A six-step digital credit evaluation process: (1) collect customer data—transaction history, payment records, enterprise scale, business status; (2) process the data via big data and machine learning to identify risk patterns; (3) build weighted credit score models; (4) assign scores to each customer; (5) classify into high/medium/low credit tiers; (6) monitor and update ratings regularly.

Cargo Retention and Enterprise-Finance Checks and Balances

IoT, big data, and AI create linkages between enterprises and financial institutions, ensuring adequate retained cargo value. Cargo tracking systems and financial docking platforms enable real-time cargo-finance information interoperability. Per the port operation contract's lien provisions, customer arrears and cargo values are tracked in real time to ensure full coverage of receivables.

Smart Contract Payment Cycle Control

Smart contracts—decentralized, traceable, and tamper-proof—address three digital governance risk domains. Data security: blockchain encryption prevents tampering and leakage. Cross-border payment: automated compliance with multi-jurisdictional regulations reduces friction. Supply chain coordination: shared digital contracts optimize logistics paths and inventory management. Implementation requires clear payment terms, embedded risk management mechanisms (auto-adjusting for disruptions), multi-party collaborative management, and continuous optimization through data feedback.

Strengthen Cargo Management Risk Prevention and Control

The three-layer defense system ensures the safety of cargo transportation operations. First, prevent cargo rights disputes by adopting standardized contract templates that avoid ambiguous ownership language, strictly controlling seal usage, and prohibiting unauthorized issuance of deposit or manifest certificates. Second, prevent illegal release through standardized lien exercise procedures and a digital "locking" function that eliminates human error. Third, strengthen process management via comprehensive quality management measures, complete documentation for all cargo movements, and regular self-inspections to detect and resolve accounting discrepancies.

Digital Technology Innovation: Blockchain Risk Governance Capacity Building

Digital technology innovation provides new means for blockchain risk governance. As a decentralized, open, and transparent technology, blockchain enhances information sharing and data credibility while reducing certain operational risks.

Rationale for Blockchain in Port Risk Governance

Blockchain addresses three pain points in port supply chains: information redundancy from incompatible systems, information asymmetry causing low transaction efficiency, and over-reliance on traditional credit systems in supply chain finance. However, blockchain introduces new risks: data security vulnerabilities from decentralized access, technical failures or operational errors, and evolving regulatory requirements. A balanced approach leverages blockchain's strengths while maintaining robust governance.

Risk Assessment and Monitoring Framework

A three-tier framework governs blockchain risks. First, evaluate commercialization risks (strategic, operational, supplier, reputational), legal/regulatory risks (policy, compliance, contract disputes), and technical risks (consensus algorithms, privacy, smart contract vulnerabilities). Second, establish comprehensive risk management strategies with classification systems and security controls. Third, implement continuous monitoring via risk early-warning mechanisms, indicator tracking, and incident response protocols. The smart contract risk-level evaluation model processes on-chain product data and external assessments to generate dynamic risk ratings.

Implementation Path

Five implementation strategies drive blockchain governance. First, identify application scenarios—supply chain operations, smart logistics—that address information redundancy and business risks. Second, participate in standards development organizations (e.g., Blockchain

Standards Committee) and conduct rigorous technology testing. Third, integrate blockchain with IoT (real-time device monitoring), smart contracts (multi-party data verification), and privacy protection mechanisms. Fourth, build a digital risk management mechanism with clear risk positioning, emergency response plans, and cross-departmental coordination. Fifth, accelerate talent development through training programs, industry-academia-research cooperation, and innovation culture cultivation.

RESEARCH CONCLUSIONS AND PROSPECTS

Study Conclusions

Singapore's digital port development offers three key insights: prioritizing digital technologies in port operations, detecting and managing holistic risks through technological innovation, and deeply embedding digital culture across all staff and processes. Digital port construction is essential for China's high-quality port development and contributes to Chinese-style modernization. Under the "dual circulation" economic model, new technologies and achievements are continuously developed and applied in ports, fundamentally transforming production and management paradigms. Digital ports form the foundation for smart ports—the more advanced stage of digital development. Operational risks and governance can no longer be addressed solely through internal enterprise financial audits; an ecosystem perspective is required for systematic risk management.

Research Prospects

As digitalization accelerates, ports—critical nodes in global supply chains—face evolving risk characteristics. Data security and privacy protection are becoming increasingly challenging as data flows intensify across operational links; any breach or tampering can cascade through the entire supply chain. Automation and intelligent technologies require robust emergency response mechanisms to handle unforeseen disruptions. Green development imperatives also add environmental responsibility to the range of port risks.

Future governance pathways should focus on three directions: strengthening data security technology development, constructing intelligent emergency response systems, and advancing green port construction with comprehensive environmental responsibility frameworks. This research not only addresses current operational risks but also provides a course for sustainable, secure, and efficient port development.

DECLARATION

Acknowledgments

None

Author contribution

Conceptualization, Investigation, Data curation, Writing—Original draft preparation, Writing—Reviewing and Editing, Supervision, Writing—Reviewing and Editing, Writing—Original draft preparation, Writing—Reviewing and Editing.

All authors have read and approved the final version.

Source of funding

2022 Shandong Vocational Education Teaching Reform Research Project (Title: Research on the Cultivation of Craftsman Spirit among Higher Vocational Students in the Era of Digital Economy, No.: 2022263); Key Education and Teaching Research Project of Shandong Province (Research on the Mechanism and Implementation Path of Digital Education in Higher Vocational Colleges Empowered by New Quality Productive Forces, 2024JXZ034); Qingdao's "Double Hundred Research Project" (Title: Research on an Innovative Integrated Regulatory Model for Containers Transporting Hazardous Chemicals in Free Trade Zones, No.: 2022-B-004).

Ethical approval

Not applicable.

Informed consent

Not applicable.

Conflict of interest

The author declares no competing interests.

Use of large language models, AI and machine learning tools

None

Data availability statement

All data and materials used in this study are derived from publicly available policy documents, institutional reports, project materials, and published literature cited in the manuscript. No additional dataset was generated.

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