

Research on Optimization Strategies for Reverse Supply Chains of Port Waste Materials and Containers from the Circular Economy Perspective

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Abstract

With the continuous expansion of global shipping volume and accelerating green low-carbon transition of ports, establishing reverse supply chains for waste materials represents a core pathway for ports to implement the 3R principles of circular economy. Domestic ports in China are currently confronted with prevalent challenges, including fragmented recycling systems, extensive sorting and disposal practices, broken resource recycling links, and insufficient coordination mechanisms among multiple stakeholders, which greatly hinder sustainable port development. This paper reviews reverse governance practices at domestic and international ports such as Ningbo Zhoushan Port, Shanghai Yangshan Port, Port of Singapore and Port of Rotterdam, and identifies replicable experiences including centralized collection, intelligent sorting, full life cycle closed-loop operation and multi-party collaborative governance. It is noted that existing practices mostly focus on fragmented improvements targeting isolated individual links. Drawing on circular economy theories, this paper integrates strengths from multiple case studies and proposes an integrated optimization system for reverse supply chains characterized by “unified network-based collection, two-tier classification, three stage closed-loop circulation and four dimensional co-governance”. A multi-dimensional governance platform integrating multi-stakeholder collaboration, digital traceability and institutional constraints is further constructed to cut operational costs of reverse logistics. This research provides theoretical support and practical solutions for the green transformation and upgrading of reverse supply chains for port waste materials and containers.

Keywords

circular economy, port reverse supply chain, waste materials, containers

1. Introduction

Global maritime trade continues to expand. As critical hubs for sea-land intermodal transport, ports generate massive volumes of end-of-life containers, port operation consumables and solid waste from port adjacent industries each year. Improving reverse supply chain systems and promoting resource-oriented recycling of waste materials have become core measures for ports to implement the reduction and resource recycling concepts of circular economy and achieve green and low-carbon transition [1-3].

At present, waste material recovery in most domestic ports is geographically scattered without unified overall management mechanisms. Sorting operations still rely on labor intensive manual work, and complete

reverse circulation chains are hard to establish. This directly brings about practical problems such as low material recycling rates, inefficient occupation of port yard land resources and high operational costs for reverse logistics, which considerably impedes the green and sustainable development of ports [3, 4].

Leading domestic and international ports, including Ningbo-Zhoushan Port and the Port of Rotterdam, have carried out pioneering practices in waste material circular governance and accumulated replicable experience. Nevertheless, most existing transformation models only cover a single waste category or one individual business link, and systematic solutions tailored to multi-category collaborative recycling for comprehensive ports in China remain absent. Accordingly, grounded in circular economy theory and targeting practical deficiencies of reverse supply chains in domestic ports, this paper integrates merits of various port practice models to build a full process optimization system. Supporting optimization strategies are proposed from four dimensions: pre-stage unified collection, mid-stage intelligent classified disposal, post-stage closed-loop resource feedback, and digital collaborative governance among multiple stakeholders. This study offers theoretical references and implementable pathways for the green upgrading of reverse supply chains for containers and various waste materials at Chinese ports [2].

2. Background

2.1 Low Utilization Rate of Port Waste Materials

The absence of coordinated management mechanisms and fragmentation of recycling systems constitute the root causes of disordered recycling and low efficiency utilization of waste materials at Chinese ports. Reverse material recycling at major domestic ports is generally disorganized, with no officially coordinated standardized recycling framework in place. Neither Tianjin Port nor Beilun Port Area of Ningbo-Zhoushan Port has set up dedicated recycling management departments or fixed collection channels for end-of-life containers, operation pallets, mooring ropes and port adjacent industrial solid waste. At present, waste material recycling services are entirely undertaken by individual scavengers and small to medium sized third-party recyclers, without unified standards for collection schedules, classification criteria or purchase prices. Meanwhile, the recycling market is strongly profit driven. Recyclers tend to collect only high value materials while discarding low value waste. Large volumes of low value port consumables and industrial solid waste are stockpiled in open air idle port areas for long periods, which not only occupies scarce port yard resources but also results in idleness and waste of stock materials [5].

The lack of standardized sorting and disposal mechanisms leads to crude sorting practices and severe resource mismatch for port waste materials. Even at benchmark ports such as Ningbo Zhoushan Port and Shanghai Yangshan Port, reverse material sorting still largely relies on conventional manual screening. Port operators only perform rudimentary classification, and there are no quantitative criteria for evaluating the reparability of end-of-life containers. Numerous slightly damaged containers with low repair costs and reuse potential are directly written off as scrap. Differentiated classification and targeted resource-oriented disposal are also absent for reusable operational consumables, including wooden pallets and used mooring ropes [4, 6, 7].

2.2 Poor Operational Efficiency

A lack of multi-stakeholder coordination mechanisms results in fragmented participants and persistently high operation and maintenance costs within port reverse logistics. The reverse supply chain for port waste materials involves multiple parties: port operators, shipping lines, port adjacent manufacturers, third-party recyclers and recycling processing plants. Nevertheless, domestic ports have yet to establish unified and interactive collaborative operational mechanisms [2, 11]. Major port areas, including Ningbo Port, Tianjin Port and Shanghai Port merely provide storage for waste materials, while recycling processors cannot obtain stable, large-scale supplies of waste feedstock. Each stakeholder operates independently, giving rise to prominent information silos and disconnected benefit distribution arrangements. Compared with highly coordinated forward supply chains in ports, reverse logistics suffers from substantially higher overall operating costs and poor economic viability [12].

The absence of an end-to-end closed-loop circulation system breaks the recycling chain of port waste materials and keeps overall resource recovery efficiency at a low level. Domestic ports record generally low

recycling rates: the refurbishment and reuse rate of end-of-life containers at Ningbo Zhoushan Port and Tianjin Port is below 35%; the recycling rate of port operational consumables stands under 20%, and the onsite resource-oriented disposal rate of port adjacent industrial solid waste is less than 15%. Ports have not built a complete closed-loop chain of “collection sorting refurbishment reprocessing resource return to port premises”, making it difficult to implement the three core principles of circular economy: reduction, reuse and resource recovery [8-10].

3. Literature Review

3.1 Recycling and Intelligent Classification of Waste Materials

3.1.1 Resource Fragmentation Theory — Lessons from the Centralized Collection Model of Ningbo Zhoushan Port’s “Blue Cycle” Project

Fragmented resource allocation constitutes a core bottleneck restricting the improvement of solid waste resource recovery efficiency. A clustered governance model with joint efforts from governments, port enterprises and environmental regulatory authorities can establish standardized reverse logistics recycling systems to realize intensive disposal and value maximization of waste resources [3].

The “Blue Cycle” comprehensive governance project for marine and port waste implemented at Ningbo Zhoushan Port serves as a typical practical case of clustered governance theory applied to port circular economy practices. Jointly initiated by the port group, maritime authorities and local government, this project builds an official standardized integrated platform for waste material collection. Following the logic of unified collection and governance, it achieves full coverage recycling for both high value and low value waste materials, offering practical references for large scale and standardized recycling of waste materials across the industry [13, 14].

3.1.2 Refined Utilization Theory — Insights from the Intelligent Classification and Disposal System of Shanghai Yangshan Port

Theories on smart solid waste governance and refined resource recycling indicate that the resource recovery efficiency of waste materials is jointly determined by classification identification accuracy and the standardization level of disposal workflows. Traditional labor intensive manual sorting is highly subjective with ambiguous grading criteria. It easily leads to unnecessary scrapping of reusable materials and severe resource loss, and fails to meet the construction requirements of modern green ports [6].

Based on smart solid waste governance theories, Shanghai Yangshan Deep Water Port has developed a systematic framework for intelligent sorting and quantitative value assessment of waste materials. Automated container inspection equipment and intelligent identification systems for consumables are deployed within the port area, alongside quantitative grading rules. End-of-life containers are categorized into four disposal tiers according to damage severity, structural safety performance and refurbishment costs: direct reuse, low-cost refurbishment, component disassembly and reuse, and complete scrapping. Targeted disposal specifications are also formulated for differentiated materials, including wooden pallets, mooring ropes, packaging consumables and port adjacent industrial solid waste, eliminating resource losses caused by mixed collection and sorting at the source [4, 15].

3.2 Enhancing Recycling Performance and Establishing Integrated Mechanisms

3.2.1 Closed-loop Reverse Supply Chain — Reference from the Full Life Cycle Closed-loop Model at Port of Singapore

A complete and durable closed-loop reverse supply chain lays the foundation for upgrading resource utilization levels. Short chain and fragmented disposal approach directly reduce resource regeneration tiers and degrade resource recovery efficiency [2].

As a global benchmark for green ports, Port of Singapore applies the 3R principles of circular economy and product full life cycle governance theory through its closed-loop operation model for containers [9]. Instead of superficial single mode scrapping treatment, the port constructs a complete resource recovery chain:

“collection of decommissioned containers — intelligent inspection and grading — refurbishment and maintenance — steel and component regeneration — resource return to port premises”. This enables cascaded utilization of waste materials. Containers in sound working conditions are refurbished and deployed for short sea feeder shipping; moderately damaged containers are disassembled to extract usable components for port equipment maintenance and site reconstruction; heavily damaged containers are dismantled for steel remelting to accomplish full loop resource circulation [6].

3.2.2 Reverse Logistics System — Reference from the Multi-party Coordination Mechanism at Port of Rotterdam

The operational performance of reverse logistics systems heavily relies on three-dimensional coordination among participating stakeholders in terms of rights and obligations, benefits and workflows. Decentralized independent operation brings about a series of problems such as redundant resource allocation, rising operating and maintenance costs and inefficient circulation systems.

The multi-party port shipping coordination mechanism adopted by Port of Rotterdam in the Netherlands well aligns with collaborative governance theories for reverse supply chains and effectively addresses common industrial bottlenecks. The port formulates unified end to end disposal standards and builds a port shipping circular industry community with clear rights, obligation allocation and shared interests. Shipping lines provide stable supplies of reverse materials such as end-of-life containers; the port supplies yard space and overall regulatory services; recycling enterprises undertake professional resource-oriented processing; logistics providers carry out dedicated reverse transport tasks. This integrated linkage mechanism streamlines redundant workflows and breaks cross-stakeholder information barriers, substantially cutting warehousing, transportation and overall administrative costs for reverse logistics [12, 16].

4. Core Findings

4.1 Case Summary and Existing Problems

Current practical practices of port reverse supply chains suffer prominent systematic defects. All benchmark cases at home and abroad only carry out partial and fragmented renovations, without forming an integrated governance framework adaptable to the operational scenarios of comprehensive ports in China. Domestic comprehensive ports handle a wide range of waste materials, mainly including three major categories: end-of-life containers, port operational consumables, and diverse industrial solid wastes generated in port hinterlands. However, existing studies lack systematic designs for the collaborative recycling of multi-category waste materials, failing to match the large-scale and diversified governance demands of waste management in domestic ports.

Furthermore, most existing practices are constrained by single-dimensional governance, fragmented theoretical implementation, and disjointed business links. They fail to organically integrate key functional modules including front-end material collection, mid-stage classified disposal, back-end closed-loop resource utilization, cross-stakeholder collaborative governance, and digital supervision.

Front-end collection theories for reverse supply chains indicate that full-coverage and large-scale material collection serves as the foundation of resource utilization. A single fixed recycling model easily leads to missed collection of low-value materials, loss of high-value resources, and disorderly stockpiling of waste. The “Blue Cycle” model of Ningbo-Zhoushan Port realizes standardized official recycling, yet it is restricted by fixed collection points, single operational modes and insufficient full-domain coverage, making it incapable of meeting the full-category and full-domain collection demands of large-scale comprehensive ports.

Integrating the strengths of the two benchmark models and adapting to the multi-category governance needs of domestic ports, this paper constructs a refined disposal system featuring intelligent identification, standardized grading and differentiated disposal. Quantitative classification criteria are formulated for different types of waste: end-of-life containers are divided into four grades of direct reuse, low-cost refurbishment, component disassembly and overall scrapping based on structural integrity, safety performance and refurbishment costs; port operational consumables are classified into direct reuse, repaired utilization, resource regeneration and abandonment; port hinterland solid wastes are processed through differentiated resource

utilization and harmless treatment paths. Meanwhile, intelligent detection and digital evaluation technologies are introduced to improve the overall resource recycling efficiency.

5. Discussion

The system proposed in this study is designed on the premises of idealized multi-stakeholder benefit symbiosis, stable waste material supply and harmonized regional environmental policies. Nevertheless, multiple external variables in practical operation may undermine its operational efficiency, representing real-world contradictions that are not elaborated in the main text.

First, market price fluctuations threaten operational stability. Market conditions for scrap steel, wooden consumables and recycled materials exhibit cyclical volatility. When market prices for recycled feedstock decline, third party recyclers and reprocessing plants show substantially reduced willingness to collect waste. Consequently, low value port consumables and industrial solid waste may once again be left uncollected and stockpiled on site. The present framework only establishes long-term cooperation arrangements via the collaborative platform, without supporting government subsidies as a safety net, which results in insufficient risk resilience against market volatility.

Second, heterogeneous regional environmental policies create regulatory constraints. Coastal and inland water ports across China fall under the jurisdiction of different provincial and municipal authorities. Marked discrepancies exist in local solid waste discharge standards, tax incentives for recycled resources, and environmental approval procedures for end-of-life container refurbishment. When the identical reverse supply chain system is replicated across regions, adjustments must be made to comply with divergent local regulatory requirements, which considerably raises transformation and compliance costs. Furthermore, transport restrictions imposed on outbound shipments of scrap steel and industrial solid waste in certain regions may disrupt the dual loop circulation of “in port backflow plus external reprocessing” and limit the scope for cascaded material utilization.

6. Conclusion

Based on the 3R principles of circular economy, this paper systematically analyzes the practical problems of domestic port reverse supply chains, including fragmented recycling systems, crude material sorting, broken circulation links, and insufficient multi-stakeholder collaboration. Drawing on practical experiences of typical ports at home and abroad, this study constructs an integrated optimization system characterized by “unified network collection, two-tier classification, three-stage closed-loop circulation, and four-dimensional co-governance”. Breaking through the limitations of existing studies that focus merely on single container materials and fragmented renovation schemes, the research incorporates the governance characteristics of government-enterprise-port collaboration in Chinese ports and adopts digital traceability technologies. It finally forms a full-chain solution adaptable to the recycled utilization of multi-category waste materials for local ports.

Nevertheless, this study mainly adopts qualitative case analysis without quantitative benefit measurement. It fails to formulate differentiated implementation strategies for different types of ports and fully consider the external impacts of market price fluctuations and regional environmental policy differences. Future research can establish quantitative evaluation models based on port operational data, refine implementation paths for different port types, and improve dynamic regulation mechanisms by incorporating external influencing factors. In addition, in-depth integration of digital technologies can optimize the full-process management and control of reverse materials, so as to further improve the theoretical research system of circular reverse supply chains for ports.

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Conflicts of Interest

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