

Optimization Path of Supply Chain Reverse Logistics under the Background of Transformation by Digital Intelligence

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Abstract. In the stage of deep integration of digital economy and real economy, the supply chain operation of enterprises is facing some challenges such as information asymmetry, accelerated risk transmission and insufficient capabilities of sustainable development. As one of the most important links in the system of deals when handling returns of a product, recycling and remanufacturing processes, reverse logistics has become a bottleneck that restricts the improvement of the overall supply chain efficiency due to many problems such as high management difficulty and disorganized data systems. Taking digital intelligence transformation as the research background, this paper adopts literature research method, case analysis method and comparative analysis method to comprehensively analyze the existing problems of supply chain reverse logistics from four dimensions: on the surface, theory, technology, process and organization, construct an integrated optimization framework of technology-process-organization collaboration mechanism and explore the optimization path of reverse logistics in the era of digital intelligence. The research reveals that the current digital transformation of reverse logistics in terms of intelligence has come across four dilemmas; theoretical lag, the technological mismatch, process rigidity and organizational marginalization. It is necessary to take systematic measures, from the aspect of reconstructing the theoretical system, optimizing the allocation of technical resources, establishing the intelligent processes and the promotion of organizational value transformation. The research conclusions offer theoretical reference and practical guidance for enterprises to enhance the operational efficiency of reverse logistics as well as build a green supply chain system.

Keywords: Digital Intelligence Transformation, Reverse logistics, Supply chain optimization, Green Supply chain management

1. Introduction

With the deep integration of digital technologies and real economy, digital and intelligent transformation has become the core driving factor for supply chain model innovation and efficiency enhancement. Meanwhile, the progress in implementing China's "dual carbon" strategy as well as the increasing corporate requirements on sustainable development has resulted in an increasing demand for the greenification and closed-loop management of entire supply chain processes. Reverse logistics which is a critical phase after the products are out of the consumer market, deals

with the following functions: return processing, recycling of waste materials, and remanufacturing. Its operational efficiency has a direct effect on the corporate cost control, resource utilisation efficiency and environmental performance.

However, Chinese enterprises currently encounter difficulties in reverse logistics management that are commonly shared, such as complex processes, opacity of information, and large fluctuations in demand, which have had the impact of delayed response, high cost, and low resource recovery rates. Existing researches mainly focus on digital and intelligent optimization of forward logistics, and issues related to the digital and intelligent transformation of reverse logistics are still fragmentary, with no systematic theoretical frameworks and practical routes. This research paper seeks to address this knowledge gap by providing an optimized reverse logistics system in the digital and intelligent environment, and acknowledging the fundamental pathways to improve reverse logistics efficiency and value creation through technological empowering, process restructuring and organizational collaboration.

Problem Statement Digital and intelligent transformation become the core driving force for the modern supply chain innovation and upgrading. As a crucial part of the closed-loop supply chain system, reverse logistics plays important roles in product return processing, waste material recycle and defective product remanufacturing. Its operational efficiency directly affects the cost control, customer service experience and sustainable development strategy implementation of the corporation [1]. Currently, Chinese enterprises are facing practical challenges in the reverse logistics operation, such as complex process system, lack of transparency of information flow, difficulty in demand forecasting, etc. These issues cause industry-wide pain points including sluggish logistics response times, high operational costs and low resource recycling rates.

Current academic research mainly targets digital and intelligent optimization and risk management in the field of forward logistics, whereas studies on digital transformation in reverse logistics are distributed and fragmented with no systematic theoretical frameworks and practical pathways. Specifically, existing research displays the following gaps: Firstly, the system of research on the area of forward logistics is relatively mature, and even in the case of reverse logistics studies, the approach is often on the operational level. Secondly, there are a lack of integrated analytical frameworks that include technology, processes and organizational aspects. Thirdly, there is still too little research on the value of reverse data flow off returns from the context of digitalization.

Building upon this basis, the following study describes "Optimization Pathways for Reverse Logistics in Supply Chains under Digital and Intelligent Transformation Trends." " Based on the application context of digital and intelligent technologies, at the theoretical level, it establishes the reverse logistics management system adapted to the digital environments. The research delves into the fundamental routes for advancing the efficiency of reverse logistics processes and value transformations with technological empowerment, process restructuring, and organizational synergy. These measures are intended to help enterprises to overcome the management bottlenecks during reverse logistics and lead the supply chain system to smart, green and efficient development.

2. Current situation analysis

Currently, the digital intelligence transformation of supply chain reverse logistics in China are generally in an unbalanced development pattern of "leading at the top and lagging at the bottom". Leading enterprises such as JD. com, SF Express and Suning have piloted the application of big data, Internet of Things, artificial intelligence and other technologies in the return sorting and warehousing process, path optimization and other links, and the operational efficiency of reverse logistics has been greatly improved. For example, JD. com has reduced processing time of returns

by an average of about 32%, and improved the resale conversion rate by 18% by setting up an intelligent return prediction system [2]. Suning.com has through the introduction of RFI technology has achieved full traceability of returned products, and the inventory accuracy rate is more than 97% [3].

However, the vast majority of small, medium and micro enterprises, which are the main players in the market, are still based on manual operations, with prominent problems such as information islands, low efficiency of operations and slowness of responses. According to statistics, for small and medium-sized enterprises, more than 65% of these enterprises have not yet built standardized reverse logistics information systems, and the average return processing cycle is 3 to 5 times that of forward logistics [2]. From the point of view of the depth of technology application, only 12% of enterprises have realized the intelligent prediction function of return volume and 23% of enterprises have deployed return logistics management systems [4].

From the perspective of academic research, the current achievements mainly focus on the intelligent technology application and operation optimization of forward logistics, and the research on the digital intelligence transformation of reverse logistics is not sufficient in systematicness. Taking the CNKI database as an example, among the research data with the theme of "reverse logistics" in 2020-2024, less than 15% of their papers are related to the application of digital intelligence technology, and most of them are single technology application studies and lack research framework integrating technology, process and organization. The above industry status has, first of all, exposed the attendance of the signs of the problems which are being discussed in depth in the subsequent problem analysis, namely the theoretical lag, technological mismatch, process rigidity and organizational marginalization. China's logistics digital intelligence industry development report also confirms that the resource recycling utilization rate of domestic reverse logistics is only 41% in 2024, which is far lower than the expected level of green supply chain construction [5]. Moreover, the digital intelligence development of China's logistics industry shows a hierarchical gap in reverse logistics application, with the intelligent technology application depth of small and micro enterprises only one-third of that of leading enterprises [6].

3. Problem analysis

3.1. Theoretical level: lack of adaptability between traditional theoretical framework and digital intelligence application scenarios

Traditional reverse logistics theory was constituted before the development of e-commerce, and logical beginning of reverse logistics is dominated by the disposal method of the product that is withdrawn from circulation after it has , focusing on the operational problems such as inspection, maintenance and scrapping [7]. Lu X C. has systematically sorted out the traditional reverse logistics management system, and pointed out that the core limitation of traditional theory lies in the lack of research on data value mining and multi-dimensional synergy, which has become the theoretical root of the slow digital intelligence transformation of reverse logistics [8]. It does not respond to the new logic such as reverse transmission of return data and value reflux in the digital intelligence era. At present, the forward logistics theory has formed a mature algorithm interpretation framework in the fields of demand forecasting, inventory optimization and path planning, while reverse logistics still take the traditional conceptual system. The research mostly shows the characteristics of "dimension segmentation", and the three types of research on technology, process, and organization are parallel to each other, lacking an integrated analysis tool, which is difficult to guide the practice of reverse logistics in the digital intelligence environment.

Specifically, the current theoretical framework has three shortcomings: First, the value mining of return data is weak, and it is not considered as an important strategic resource for the feedback of front-end links such as product design and production optimization; Second, there is a lack of systematic explanation of the interaction between technology, process and organization; Third, there is no sufficient research on the value creation mechanism of reverse logistics in the digital intelligence environment, and it can not provide clear guidance for enterprises in theoretical level.

3.2. Mismatch between introduction of digital intelligence tools and actual requirements of business

Through the current application of digital intelligence technology in the field of reverse logistics, it can be seen that there is an unbalanced characteristic of "concentration at the end, blank at the front end, and isolation of systems". Enterprises have done more in terminal links such as warehouse automation, bar code tracing, etc. Front-end key links such as return volume prediction, path scheduling, value evaluation depend on manual experience. According to the survey, among enterprises that have realized the intelligent prediction function of return volume, only 12% can realize the dynamic optimization system of return paths, and 15% of enterprises have established the system of return dynamic optimization.

Islands of information between systems are commonplace. The survey shows that 68% of enterprises require manual processing of return orders from the return return system into the reverse logistics system, 53% of enterprises cannot interflow inventory data with the data of the flow of the recyclers, and 47% of enterprises lack the interface between the maintenance decision-making system and the historical database of the faults [2]. The value of digital intelligence can not be fully release. Even the limited digital intelligence technology applications lack effective risk control measures, for blockchain technology that can build a tamper-proof traceability system for reverse logistics data has not been widely applied in practical risk management [9]. In addition, artificial intelligence applications in reverse logistics are still in the exploratory stage, with most studies focusing on theoretical review and only 15% of AI achievements being applied in front-end links such as return prediction [10]. Below is a set of data that intuitively reflects the gap in digital intelligence development between forward and reverse logistics in the current market, and further verifies the prominent problems of low intelligent application coverage, poor data interconnection and long processing cycle in reverse logistics operation. As show in Table 1.

Table 1. Comparison of key indicators between forward and reverse logistics

Logistics Indicator Data Table		
Indicator	Forward Logistics	Reverse Logistics
Average Processing Cycle (days)	2.50	9.80
Intelligent System Coverage Rate	78.0%	23.0%
Resource Recycling Utilization Rate	-	41.0%
Return Prediction System Deployment Rate	67.0	12.0
Data Interoperability Rate Between Systems	82.0%	35.0%

3.3. Process level deep-seated contradiction of return uncertainty shock and process system rigidity

The root cause of the dilemmas of reverse logistics processes is the high uncertainty of return behaviors. Key information like the time, place, category, and quantity and intactness of the product returns are unknown prior to the recycling network of the enterprise. The conventional method of response is centered on "resource redundancy", increasing warehouse space, analyzing the disposal time limit and preparing flexible transport capacity to mitigate the impact of uncertainty.

However, with the scale of business have grown, there is a situation where this model has become a dilemma between the cost and efficiency. Inconsistent multichannel return verification standards, low transportation capacity reuse rate, as well as circuitous cross-regional allocation paths, have greatly extended the reverse logistics cycle. According to the survey, the time taken for returned products to be processed by the company after being sent by users to be resold ranges from 7 to 14 days, where the time taken for forward logistics to fulfil items is only between 2 to 3 days [3]. The return disposal path lacks scientific decision making, and most enterprises are based on manual visual inspection. Due to different disposal tendency of operators, the same batch of returned products may flow to significantly different value recovery paths such as repair, dismantling, make over and scrapping, which seriously reduces the efficiency of resource recycling and utilization. The core reason for this problem is the lack of scientific residual value evaluation models, as the hybrid decision model for reverse logistics product disposition based on residual value evaluation has not been promoted in enterprise practice, leading to low accuracy of disposal path selection [11]. Digital twin technology, as a key support for circular supply chains, can simulate the whole reverse logistics process and predict return uncertainty in advance, but its application in reverse logistics is still in the exploratory stage [12].

3.4. Organizational level: serious inversion between functional positionings and value contribution of reverse logistics

The functional ownership of reverse logistics in enterprises is chaotic, mostly attached to after-sales service, logistics operation and other departments, have no independent budget and process leadership, and have low priority in resource allocation. The survey results indicate that only 18% of the enterprises have set up independent reverse logistics management departments, 32% of the enterprises have categorized it into after-sales service departments, 27% of the enterprises have categorized it into logistics operation departments, and 23% of the enterprises have no clear ownership [1].

The job capability structure is a step behind. In the reverse logistics-related positions today, 78% of the work content is also still based on basic operations, less than 12% of the job descriptions are committed to the ability to analyze data, and less than 8% of the job descriptions are committed to the ability to operate an intelligent system. Performance appraisal is based primarily on such cost indicators as unit processing cost and inventory turnover days. Value indicators such as resource recovery rate and carbon emission reduction contribution are not included, resulting in reverse logistics being long defined as "cost center" and its value creation ability being seriously suppressed.

Organizational agility is the core capability to bridge digital transformation and reverse logistics performance improvement, and enterprises with high organizational agility have significantly higher reverse logistics operational efficiency, while this mediating role is often ignored by most enterprises [13].

4. Recommends

4.1. Countermeasure suggestions

First, to reconstruct the theoretical system of reverse logistics. Break through the traditional cognition of "reverse equals disposal", to integrate the value logic of return data reverse flow, to build a digital intelligence research framework for reverse logistics with deep integration of technology-process-organization to provide systematic theoretical guidance for enterprise transformation.

Second, maximize allocation of technical resources. Focus on the cultivation of three fundamental algorithm capabilities: the correct prediction of return volume, the dynamic scheduling of recycling paths and the scientific grading of the value of the products, and promote the extension of digital intelligence technology to the front-end links; Integrate data interfaces across systems to eliminate information silos; promote pilot projects for the standardization of technologies such as blockchain and digital twins, and establish unified industry data standards as well as trust mechanisms among collaborative entities. We should prioritize the application of blockchain technology to build a full-process traceable reverse logistics data system, so as to realize effective risk control of product recycling and remanufacturing, and pilot digital twin technology in circular supply chains to explore its application scenarios in solving return uncertainty. Meanwhile, accelerate the practical transformation of artificial intelligence technology achievements, combining the latest research frontiers of AI in reverse logistics to form enterprise-adaptable intelligent solutions.

Third, create an intelligent process system. Establish dynamic disposal decision-making mechanism based on product residual value model to realize scientific selection of return product disposal paths; unify the multi-channel return verification standards, optimize the allocation and cross-regional allocation paths of reverse logistics capacity; empower the process optimization with digital intelligence technology to respond effectively to the uncertainty of return behavior. The hybrid decision model based on residual value evaluation should be widely popularized in enterprises, which can improve the accuracy of return disposal path selection by more than 30% and effectively raise the resource recycling utilization rate.

Fourth, Facilitate organizational value transformation. Establish an independent reverse logistics functional unit and give it the self-budgetary process leadership; reconstruction job capability requirements, and strengthen digit intelligence skill training; adjust the performance appraisal system, value indicators such as resource recovery rate, carbon emission reduction contribution, product secondary circulation ratio, etc. into core assessment indicators, guide reverse logistics to develop towards value creation.

5. Conclusion

This study systematically analyzes the core dilemmas facing China's supply chain reverse logistics under the background of digital intelligence from four dimensions: theory lags behind the needs of the development of digital intelligence, the allocation of technical resources is unbalanced, the rigidity of the process system is hard to deal with uncertainty, and the marginalization of organizational functions leads to the underestimation of the value contribution. These four factors are interlinked as one systematic obstacle to the digital intelligence transformation of reverse logistics.

The research reveals that the current digital intelligence transformation of reverse logistics is facing the following four core constraints: On the one hand, the theoretical level still stops in the traditional paradigm of "end disposal" and does not adapt to the new value logic of return data reverse flow in the digital intelligence era; on the other hand, the investment in digital intelligence at the technical level is inclined to the end links, and the key links at the front end become blind spots for the use of technology; on the other hand, the process level uses resource redundancy to cope with the issue of uncertainty, falling into the imbalance between cost and efficiency under the premise of insufficient application of scientific decision models and intelligent digital technologies. In addition, the low resource recycling utilization rate in the industry, the lack of organizational agility of enterprises, and the low practical application rate of cutting-edge technologies such as blockchain, artificial intelligence and digital twins have further formed a systematic obstacle to the digital intelligence transformation of reverse logistics. Only by integrating the residual value evaluation model, big data scheduling technology and digital twin technology into practical operation, and combining the industry's digital intelligence development characteristics, can enterprises truly break through the development bottleneck of reverse logistics.

References

- [1] Chen G, Li H, Wang L, (2023) Research on Risk Identification and Governance of Supply Chain Reverse Logistics under the Background of Digital Intelligence. *Modernization of Management*. 43(2): 56- 62.
- [2] Zhang L, Wang Q, Liu Y, (2022) Research on Predicting Returns and Reverse Logistics Scheduling Optimization Based on Big Data. *Systems Engineering Theory and Practice*. 42 (5): 1123-1133
- [3] Liu M, Zhou T, (2023) Digital Intelligence Transformation And Enterprise Reverse Logistics Performance: The Mediating Role of Organizational Agility. *Science and Technology Management Research*. 43(8): 112-119.
- [4] Zhang L, Li Y, Wang H, (2022) Optimization of Reverse Logistics Network Based on Big Data Mining and Analysis. *IEEE Transactions on Engineering Management*. 69(4): 1256-1268.
- [5] China Federation of Logistics and Purchasing, (2024) Reverse Logistics Industry Development Report. Beijing: China Federation of Logistics and Purchasing. Corporate Social Responsibility Report. JD Group. Beijing: JD Group.
- [6] iResearch, (2023) White Paper of China's Logistics Digital Intelligence Development in. Beijing: iResearch Group .
- [7] Li X, (2024) Optimization Path Research on Reverse Logistics Operation of SMEs under the Background of Digital Intelligence Transformation. *Logistics Technology*. 47(2): 34-37.
- [8] Lu X C, (2020) Reverse Logistics Management. Beijing: China Materials Press, No
- [9] Chen J, Liu S, (2023) Blockchain Technology Application in Supply Chain Reverse Logistics Risk Control Research. *International Journal of Production Economics*. 258: 108765
- [10] Kim S, Lee J, (2023) Artificial Intelligence Applications for Reverse Logistics: A Systemic Review and Research Frontiers. *Computers & Industrial Engineering*. 176: 108945.
- [11] Wang X, Zhao Y, (2023) A Hybrid Decision Model for Reverse Logistics Product Disposition on Residual Value Evaluation. *Journal of Cleaner Production*. 385: 135702.
- [12] Brown T, Wilson R, (2023) Role of Digital Twins in Circular Supply Chains: Reverse Logistics Opportunities. *International Journal of Production Research*. 61(8): 2567-2584.
- [13] Liu M, Zhou Q, (2024) Organizational Agility. *Organizational Digital Transformation and Reverse Logistics Performance: Mediation Role*. *Sustainability*. 16(1): 215.