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Research article

Research on integrated inventory transportation optimization of inbound logistics via a VMI-TPL model of an existing enterprise

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Abstract: Third-party logistics companies face a challenging task in minimizing inventory transportation costs due to the complexities of managing numerous suppliers. Effectively optimizing costs becomes a formidable problem for such companies. This empirical research has yielded strategies for minimizing the inventory transportation cost specifically for company D. Through a rigorous optimization process, the findings presented in this paper demonstrate an average reduction of 7.18% in company D's inventory transportation cost. By jointly optimizing inbound logistics inventory transportation under VMI-TPL mode, this study extends the theory of supplier managed inventory and improves the inbound logistics mode. The results of this study can provide quantitative support and decision-making references for the project operation management of company D and similar enterprises.

Keywords: supplier inventory management; third-party logistics; milk run inventory transportation optimization; decentralized distributed inventory transportation optimization

1. Introduction

G company is a leading electronic product manufacturing enterprise, specializing in the components production of original equipment manufacturer (OEM) for mobile phones including microphones, speakers, vibrating motors, antennas, and various sensor modules. They also manufacture a range of smart devices including headphones, smart speakers, smart bands, smartwatches, game consoles and peripherals, augmented/virtual reality (AR/VR) and smart TVs. G company's impressive customer base includes some of the world's most renowned enterprises such as Apple, Samsung, Huawei, Xiaomi, Microsoft and SONY. With over 90,000 employees, G company has established itself as a prominent player in the industry, with an annual turnover of over USD 10 billion. Their adoption of the vendor-managed inventory (VMI) model based on the management of third-party logistics (TPL) with D company.

The passage focuses on the challenges faced by a company identified by the letter D in terms of reducing the costs for their customers. It was discovered that the TPL company was only responsible for inventory management at the VMI warehouse and not involved in the supplier's parts or materials logistics. To address this, D company extended its services to include the entire supply chain, including parts transportation. However, they encountered issues with the cost and efficiency of the supply chain due to the different delivery frequencies, quantities and logistics service providers chosen by the suppliers. To overcome these challenges, D company integrated front-end supply logistics into their service scope by collecting goods. They employed two methods of cargo collection based on supplier distribution, goods quantity, transportation resources and industry experience. For regions within 200 km from the VMI warehouse, the way of recycling was adopted, while in regions far from the VMI warehouse and with a relatively concentrated distribution of suppliers, decentralized and centralized distribution was adopted. The integration of the front-end supply chain was achieved through these two methods of cargo collection, which significantly reduced the overall cost of the supply chain.

Furthermore, the rapid changes in the mobile device market posed additional challenges for VMI operations and the flow of goods under the VMI-TPL mode. The paper addresses issues such as cycle path planning, the quantity and timing of pickups and the optimization of decentralized assembly. Additionally, the lack of scientific judgment and guidance to facilitate adaptation to a dynamic market and supplier changes was identified as a problem. To address these practical problems, we aimed to study and solve two sub-problems: the optimization of milk-run inventory transportation under the VMI-TPL mode and the transportation optimization of decentralized and distributed inventory under VMI-TPL mode. By applying logistics organization management and supply chain management theories and methods, the study will provide valuable recommendations for D company to enhance their supply chain efficiency and reduce logistics costs.

In conclusion, the paper emphasizes the importance of joint optimization of inventory transportation under the VMI-TPL mode for milk run and decentralized aggregation to effectively respond to market and supplier changes. This optimization is crucial to improving the overall supply chain operations and cost-effectiveness for company D.

2. Materials and methods

2.1. Background

TPL refers to an independent legal entity that provides professional logistics services to business, including warehousing, transportation and distribution. It is important because it allows companies to outsource logistics activities that are not part of their core business, enabling them to focus on their core competencies, such as research and development, production and sales. This can lead to improved efficiency and competitiveness. TPL and supplier-managed inventory are mutually dependent and symbiotic in the supply chain. Kuk proposed three levels of integration based on performance indicators and parameters [1]. At the lowest level, suppliers seek TPL plans with the lowest prices, resulting in multiple logistics service providers. At the next level, TPL plans provide inventory storage node services on top of transportation services. Finally, strategic alliances are formed through the integration of TPL plans and suppliers, with logistics service agreements being signed after integration [2]. Sha and Zheng conducted a study on the different subsystems of the VMI model and analyzed the profit fluctuations of enterprises in a supply chain with members of varying characteristics under different conditions [3]. They revealed the internal contradictions of VMI in the areas of improving supply chain efficiency and coordinating supply chain members. This highlights the importance of introducing TPL under the conditions of VMI model. The Karimi et al. study indeed focused on analyzing service, price and inventory decisions under the conditions of retailer competition and cooperation in a VMI model [4]. They established a Stackelberg game model with the manufacturer as the leader and the retailer as the follower and used a Stackelberg-Nash equilibrium algorithm to analyze the factors that influence competition and cooperation between manufacturers and retailers in a VMI model. Their results highlighted the potential benefits of integrating TPL into the VMI model to achieve better coordination and efficiency in the supply chain. Tirkolaee et al. proposed three levels of the supply chain to address the sustainable supplier selection problem; a novel hybrid approach based on fuzzy logic was implemented. They applied the fuzzy analytic network process method to ranking criteria and sub-criteria; the fuzzy decision-making trial and evaluation laboratory was applied for the identification of the relationships among the main criteria, and the fuzzy technique for order of preference by similarity to ideal solution was applied or prioritizing the suppliers [5].

Inbound logistics is an essential aspect of manufacturing, and the automobile industry has been studying it for quite some time due to its high standardization and large product volume [6]. Inbound logistics can be categorized based on different observation perspectives, such as order mode, inventory upper and lower limit mode, quantitative mode, timing mode and Kanban mode [7]. The in-factory logistics executor's perspective can divide inbound logistics into supplier direct delivery, manufacturer self-delivery and TPL delivery. Kanban distribution is a type of timed distribution that pursues the minimum limit of line materials to meet production demand, i.e., a non-stop line. This purpose is achieved through the optimization of the path, packaging, loading and unloading and other links [8]. Kanban mode is particularly useful for supporting flexible production, and it has become an essential element in the automobile industry due to the growing trend of automobile customization. However, the restriction conditions of the Kanban mode are also clear, and it is only possible to implement high-frequency, whole-truck in-plant distribution and its flexible planning due to the rapid development of the automobile industry and the large volume of automobile parts. Scholars have considered time-discrete regulatory systems with spline entries. They introduced a new regression model for these particular two-modal systems that allows us to determine the unknown system parameters by applying the multivariate adaptive regression spline technique and the newly developed conic multivariate adaptive regression spline method [9]. They also presented the concept of fuzzy target-environment networks and various fuzzy possibilistic regression models. The relationship between the targets and/or environmental entities of the regulatory network has been given in terms of a fuzzy model [10]. They introduced and analyzed robust time-discrete target–environment regulatory systems under polyhedral uncertainty through robust optimization. Robust optimization has reached a level of great importance as a modeling framework for eliminating parametric uncertainties, and the integration of uncertain data is of considerable importance for the model's reliability of a highly interconnected system [11].

The milk run is a logistical mode of transportation that involves picking up goods from multiple locations in a circular route [12], similar to the daily milk collection from scattered pastures. This transportation mode has been applied in the supply chain field and involves several elements, such as the support of an information system for monitoring and status updates, accurate production planning, and reasonable circular route planning. By using this mode, transportation with a high frequency, a small batch and multiple time windows can be achieved, ultimately reducing the transportation cost of single parts, improving inventory turnover and saving inventory costs [13]. However, this mode is more dynamic and requires constant optimization and adjustments to ensure its optimization [14]. Overall, the milk-run mode is an effective transportation mode that can significantly improve the efficiency of inbound logistics in manufacturing enterprises.

The decentralized distribution mode, which is similar to the distribution center concept for the express industry, is rarely used in the automobile industry. The idea of distribution centers for Hollywood movies was proposed by Woolley et al. [15]. Over time, distribution centers have become an important node in the logistics supply chain to achieve the "last kilometer" in the express industry. In contrast, decentralized aggregations focus on cargo collection, which is the "first kilometer" aggregation. By gathering dispersed goods and then transporting them to the destination by vehicle, the cost of the entire transportation process can be effectively reduced, which is also the primary objective of decentralized aggregations [16]. Due to the complexity of the problem, progress in related studies was limited for many years thereafter. This problem centers around logistics route planning and is considered to be a classic logistics operation-type research issue [17]. As logistics supply chains have developed, research methods have deepened and supply chain collaborative optimization has become increasingly necessary, research into the joint optimization of inventory transportation has continued to evolve. Building on vehicle routing problem (VRP) research, the inventory routing problem (IRP) was introduced by Lukinskiy et al. [18]. Another group incorporated inventory costs into a transportation optimization model and discovered that an allocation strategy that considers inventory costs can lead to more than 6% cost savings compared to a strategy that only considers transportation costs, joint optimization model of supply chain inventory and transportation for retailers experiencing demand fluctuations based on replenishment strategy, they adopted a calculation method that separated the model into inventory and transportation phases to solve the problem [7]. Related to solving IRP models using branch-cutting algorithms [13], which were further studied by Lukinskiy et al.

As research into joint optimization of inventory transportation continues to deepen, the construction of optimization models has become increasingly diverse, complex and realistic. Some researchers have attempted to minimize inventory and transportation costs while ensuring that service constraints are met. They proposed an optimization model for integrated inventory and transportation schemes for logistics systems with single-echelon and multi-facility service components based on time-based service-level constraints [19]. Darmawan et al. considered the overall coordination and control of inventory across the entire network in a network-based supply chain and solved the problem of inventory sharing and transfer in network nodes by using heuristic algorithms to achieve the lowest total cost of the entire supply chain network [20]. Sadeghi et al. began studying a joint optimization model of inventory and transportation based on the VMI model and the improved particle swarm optimization algorithm to solve the fuzzy demand problem [13]. Li et al. developed an inventory route optimization model based on the ant colony algorithm for the retail supply chain, also incorporating TPL [21]. Poorbagheri et al. extended the supply chain system based on the VMI model from two to three levels and calculated the optimal replenishment strategy of retailers using genetic algorithms [22]. Pervin et al. proposed a deterministic inventory control model with deterioration, and the deterioration rate follows stochastic deterioration, especially Weibull distribution deterioration. A time-dependent demand approach has been introduced to show the applicability of their proposed model [23].

2.2. Methodology

A large number of domestic and foreign literature and materials related to joint optimization of inventory transportation under the VMI-TPL mode are collected, read and analyzed. The focus of the literature review is on supplier-managed inventory and TPL, inbound logistics and the joint optimization of inventory transportation. The findings of the literature review are used to determine the research problems of this paper and provide theoretical basis and support.

Mathematical modeling, which is used to establish a mathematical model for inventory transportation joint optimization under the two modes of milk-run and decentralized aggregation. The research begins with a qualitative analysis of the literature related to the joint optimization of cargo flow inventory transportation under the third-party-management VMI mode. Then, on the premise of qualitative analysis, an optimized 0–1 integer programming model is established, and relevant problems are solved and verified using the simulated annealing method, operations research method and other relevant solving methods.

Combines the established mathematical model with the project operation of D company based on the VMI-TPL mode, the optimization model has been constructed for the two inbound logistics modes of the milk run and decentralized distribution that are actually used in this project, and the actual operation data have been verified and analyzed. The effectiveness of the joint optimization of inventory transportation for the two modes is further verified, and reliable scientific guidance for the subsequent operation of the project is provided.

3. Problem analysis

The inventory transportation system operated by D company mainly consists of three parts. First, there is the incoming logistics of parts, which involves the transportation of parts from suppliers to the VMI warehouse. Second, the VMI warehouse provides parts storage, quality inspection, labeling, sorting, packaging and other related services. Third, there is the distribution between the VMI warehouse and the production workshop. The distribution between the VMI warehouse and the production workshop is determined by the customer G company based on the workshop shift and production plan, and it is therefore outside of the scope of this study. This paper focuses on the joint optimization of inventory transportation in the front-end supply logistics and VMI warehouse inventory transportation system. The project currently involves over 400 domestic and foreign suppliers, nearly 300 of which have a stable supply quantity, and nearly 20,000 kinds of materials. Depending on the geographical distribution and quantity of suppliers, D company adopts different organizational modes for the front-end supply logistics of incoming materials, such as the milk run, decentralized aggregation or direct transportation.

(1) Milk-run mode. For suppliers within 200 km of the VMI warehouse, the collection of goods is carried out in the way of a milk run [24]. Currently, the suppliers involved in milk run are mainly concentrated in Weifang city, where the VMI warehouse is located, as well as the nearby Qingdao city. The revolving vehicles leave the VMI warehouse at the set time and pick up the goods from each supplier along the revolving route. After completing the pickup, they return to the VMI warehouse.

(2) Decentralized aggregation mode. For areas far away from the VMI warehouse and given dense distribution of suppliers, the method of decentralized aggregation is adopted to collect goods. Suitable collection points are found within the region to collect goods first, and then the goods are transported to the VMI warehouse by cargo. At present, the distribution mainly involves the Yangtze River Delta, Zhejiang province, Pearl River Delta and other regions. Figure 1 shows the inventory transportation system of D company [25].

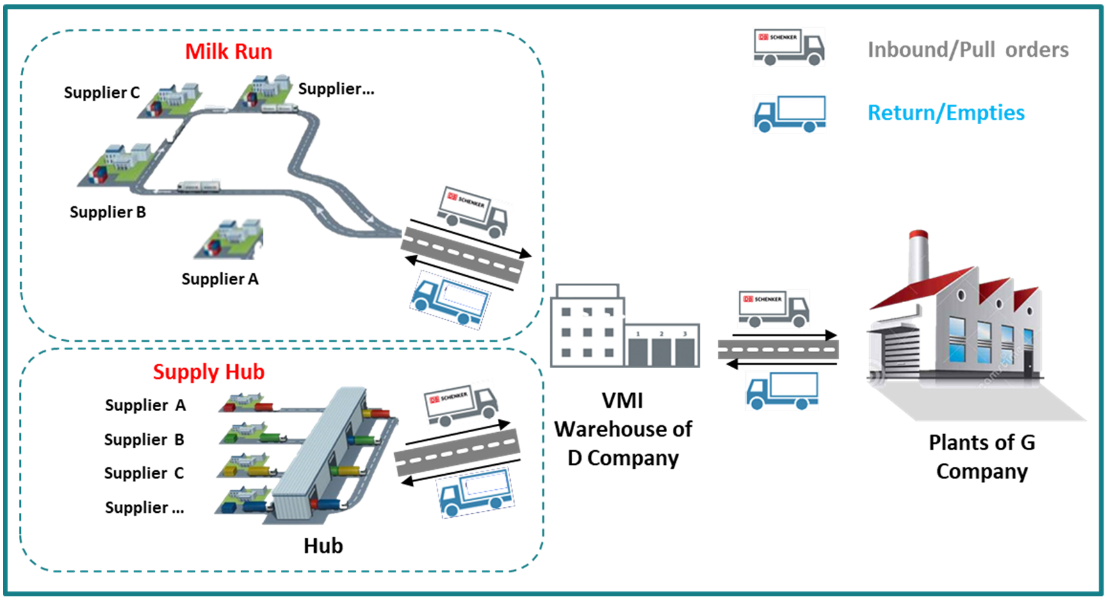

Figure 1. Transport and inventory system of D company.

3.1. Milk-run inventory transportation problem

As mentioned above, the cyclic pickup system is currently operating with a cycle range of 200 km. However, there are several problems that have arisen during the actual operation. First, the path planning for the cycle pickup is not carried out in a reasonable manner. The current strategy is to prioritize collecting goods from nearby locations and filling up the truck before moving on to the next location, which lacks a scientific approach to path planning.

Second, the guiding principle for collecting goods is based on the idea that the larger the quantity of goods collected, the lower the transportation cost. However, this approach has led to larger quantities of goods being collected and longer cycle times for the delivery of goods. The inability to adjust the quantity of goods collected flexibly has resulted in a lack of flexibility in the allocation of transportation resources. This, in turn, has led to increases in inventory, inventory turnover days and inventory-related costs, such as inventory stagnation funds and storage rent.

Changes in the market and procurement strategies have led to changes in the order quantity and suppliers, which necessitate changes in the cycle route. The existing management mode of milk run is unable to deal with these changes quickly and effectively.

3.2. Dispersed and distributed inventory transportation problem

D company heavily relies on TPL companies to carry out decentralized and distribution operations, which provides an abundant pool of transportation resources. Despite this, there are challenges in fully optimizing these resources to achieve supply chain optimization objectives.

The quantity of goods collected theoretically determines the cost of collection, and the current strategy emphasizes larger quantities to lower costs. However, this approach results in a large quantity of goods collected and longer collection times. Large volumes of goods received by the VMI warehouse also increases inventory turnover days, as shown in Figure 2.

Additionally, there is no scientifically determined collection model, and the large model strategy leads to longer collection times and increased warehouse pressure. Furthermore, the current management strategy is unable to respond effectively and quickly to dynamic situations, such as changes in order quantity and suppliers. This inability to adapt effectively to changes has become a significant obstacle in project operations.

3.3. Inbound logistics consolidation model

To address these problems, D company could consider implementing a more scientific and flexible collection model based on data analysis and optimization. For example, they could use data analytics to identify the optimal collection routes based on factors such as distance, traffic conditions and quantity of goods, rather than just relying on a simple "near-to-far" strategy. This would help to reduce the collection time and improve the efficiency of the supply chain. The data in Figure 2 come from the real data of D company.

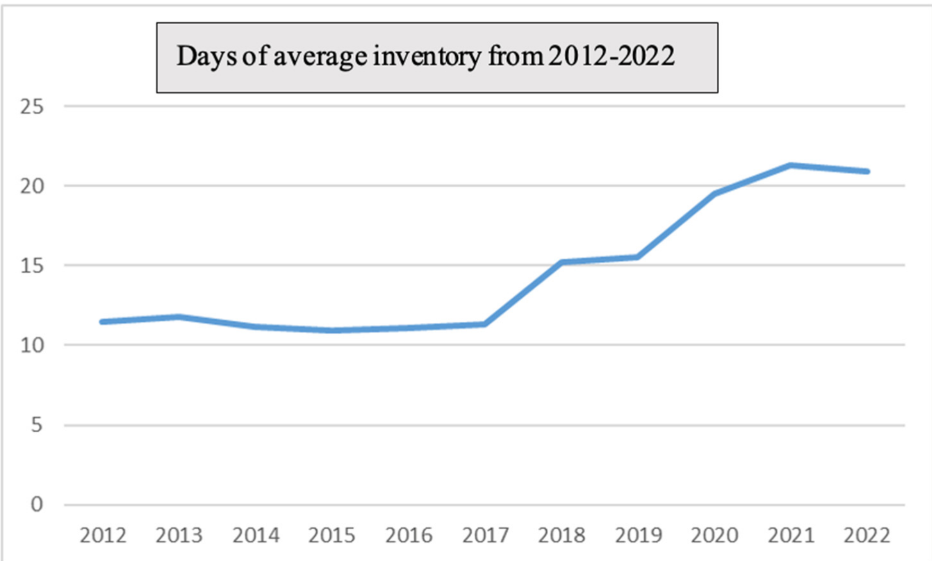

Figure 2. Days of average inventory from 2012–2022.

It is evident that the reasons behind these challenges are twofold. First, business management relies heavily on previous operational experience, and there is room for improvement in the application of scientific methods. Consequently, there is a lack of quantitative analysis of the problems associated with goods flow management, such as the circular pickup, the milk run and decentralized allocation, which hinders effective optimization.

Second, cost optimization is not considered from the perspective of the entire supply chain. Although the circular pickup, milk-run and decentralized allocation modes may reduce transportation costs, they indirectly lead to an increase in inventory costs. The inherent trade-off between transportation and inventory costs is not fully understood, which prevents the effective reduction of the overall supply chain costs. These issues will be addressed further in the remaining sections of this article. In order to optimize the inbound logistics under the VMI-TPL mode, it is necessary to adopt scientific and quantitative methods to analyze and optimize goods flow management. The traditional experience-based approach is no longer applicable to the rapidly changing market and the increasingly complex supply chain environment. Data analysis and optimization tools such as big data analysis, simulation optimization and intelligent decision-making systems can effectively improve the efficiency and accuracy of decision-making, as well as be used to achieve the goal of cost reduction and service improvement in inbound logistics.

The integration of transportation and inventory management is crucial for the optimization of inbound logistics under the VMI-TPL mode. In order to achieve a balance between transportation cost and inventory cost, it is necessary to scientifically determine the optimal aggregate model, taking into account factors such as transportation capacity, inventory turnover rate and order frequency. Through the integration of transportation and inventory management, the aggregation operation can be more flexible and efficient and the overall cost of the supply chain can be effectively reduced.

Finally, in the face of dynamic changes in the market and the supply chain, it is necessary to establish a responsive and flexible management mode to adapt to changes quickly and effectively. Through the use of real-time monitoring and analysis tools, such as Internet of Things technology and blockchain, the supply chain can be more transparent and information can be shared in a more timely and accurate manner, which is conducive to rapid decision-making and adjustment in response to changes. In addition, it is necessary to establish a risk-management system to deal with unexpected situations and reduce the impact on the supply chain.

The TPL company D is not only the participant of the supply chain, but it also acts as the "logistics tool" of the supply chain operation connection. G company relies on D company's logistics information management system to realize the information distribution and sharing of the front-end supply chain, thus realizing the real-time update and tracking of the entire chain of information, including the forecasting, production, shipping and in-transit and VMI inventory, as well as further realizing the deep integration of the whole front-end supply chain based on the VMI-TPL mode. Based on the integration of VMI-TPL, the supply front-end can realize the inbound logistics in the mode of goods aggregation. Under the milk-run mode, there are altogether 19 suppliers involved at present, mainly distributed in Weifang city and Qingdao city. The decentralized pooling mode involves 198 suppliers, which are mainly distributed in Beijing city, Tianjin city, Hebei province, the Yangtze River Delta and the Pearl River Delta. According to the distribution of suppliers, a total of four front-end warehousing centers have been setup, among which, nine suppliers are involved in the Langfang city warehousing center. The cargo center in Kunshan city involves 58 suppliers; Yiwu city cargo center involved 16 suppliers; Dongguan city cargo center involves 115 suppliers. Based on the operation arrangement and actual operation data of the above two modes of goods flow aggregation namely, milk-run and decentralized aggregation, and combined with factors such as the VMI warehouse, transportation resources and geographical location of suppliers, necessary information and element support can be provided for the further quantitative analysis of problems under the current operation mode and joint optimization of inventory and transportation. Figure 3 shows the integration mode for the inbound logistics.

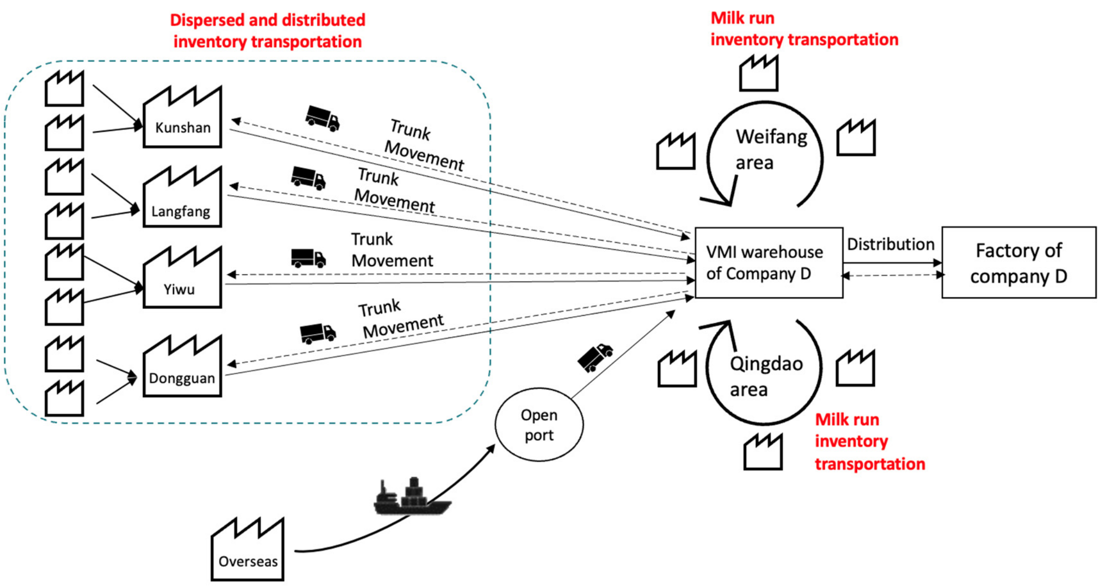

Figure 3. Inbound logistics consolidation model for D company.

This paper examines a case in which a VMI-TPL inbound logistics system is utilized, comprising the manufacturer, G company, TPL service company D and various suppliers across the country. The logistics system operates as follows:

(1) G company initiates the demand and transmits real-time data through the electronic data interchange (EDI) between their enterprise resource planning (ERP) system and D company's warehouse/transportation management system (WMS/TMS). This includes G company's future demand forecast data, production plan, material requisition orders and other relevant information.

(2) As the manager of the front-end supply chain, D company receives the demand and forecast information from G company and distributes it to all suppliers on the WMS system platform. The suppliers are provided with exclusive accounts to query their inventory data, incoming and outgoing records, demand forecast and other information in the VMI warehouse in real time. This allows for effective guidance of the follow-up production and delivery work.

(3) After receiving the demand and forecast information, the supplier prepares the goods and submits information such as the estimated spare parts preparation time and goods quantity to the information system platform.

(4) D company arranges transportation resources to pick up the goods from the supplier and ships them to the VMI warehouse, as based on the supplier's stocking condition and the way of collecting the goods possessed by the supplier. Transport information is updated in the TMS module of the information system platform to ensure real time monitoring of the transport status.

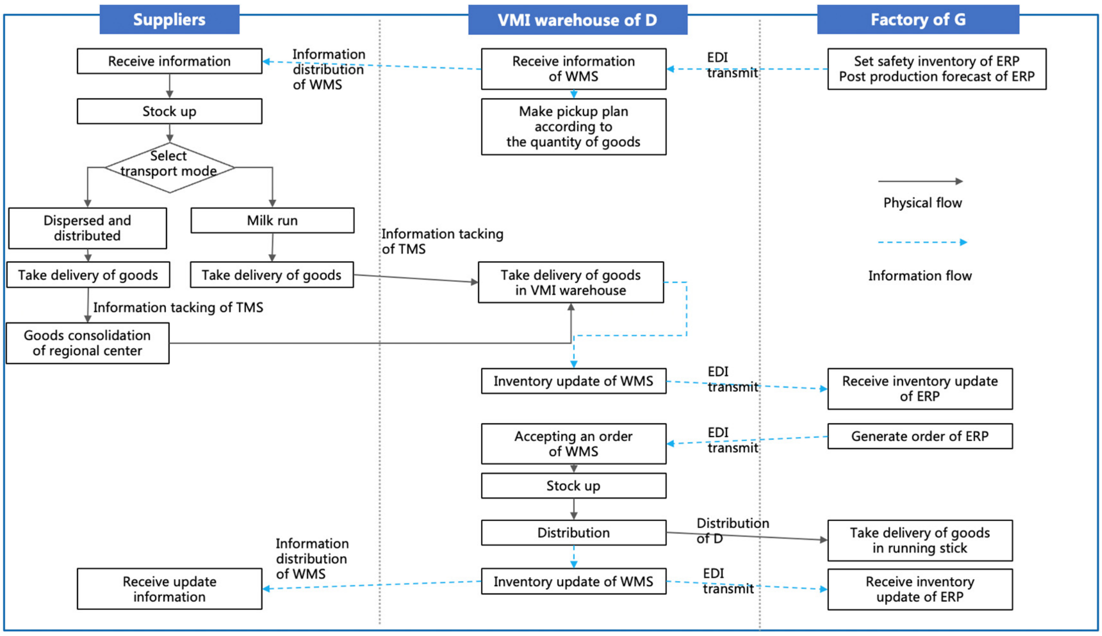

Figure 4. Operation process for inbound logistics.

(5) D company delivers the corresponding parts to G company's factory according to G company's production plan, material requisition demand and other information. The outbound order information and inventory update information are transmitted between D company's WMS and G company's ERP by EDI.

From the above process description, the TPL company D plays a crucial role in the operation and management of the entire front-end supply chain. The optimization of inventory transportation by D company is thus essential for the cost control of the entire front-end supply chain. Through the complete information platform, information sharing and transparency in the front-end supply chain are achieved, providing necessary conditions for the realization of goods flow in the supply front-end set and system and data-level support for the overall optimization of subsequent inventory transportation. Figure 4 shows the operation process for warehousing logistics.

4. Results

4.1. Milk-run stock transportation

D company manages 284 suppliers and four collection centers, of which 19 are suppliers operating the milk-run mode, and another 198 are suppliers following a "manufacturing enterprise-collection centers-D company" model. The 19 suppliers operating the milk run are all located in Shandong province, among which 12 are located in Weifang city and seven are located in Qingdao city. The transportation distance is within 200 km, which meets the research standards defined. The data in Figure 5 come from the real data of D company.

Table 1. Symbols of mathematical model.

Set			
Tc(n)	Total cost	I	Inventory cost
n	Set of suppliers	C	Transportation cost
Parameters			
k	Number of trucks		
h	Unit cost of goods storage		
q	Order of Suppliers		
u_{ri}	Supply quantity of supplier *i*		
C_{kij}	Variable transportation cost from point *i* to *j*		
E_{kij}	Fixed cost from *i* to *j*		
Y_{kij}	0–1 variable that determines whether complete transportation		
Q_k	Max loading weight		
V_k	Max loading cubage		
v_{ri}	Goods of cubage		
$d_{(i-1)i}$	Distance from *i*–1 to *i*		
d_{0n_k}	Distance of Supplier n_k from D to VMI warehouse n_k means number of suppliers		
Dk	Max distance		
L	Total number of suppliers		
S_i	Actual operating time		
bi	Scheduled operating time		
Ti	Max operating time		
ε	Tolerance value		

After defining these parameters, a route with the lowest total cost is solved according to various restrictions and conditions of D company's milk-run inventory transportation scheme. Therefore, the following model of the milk-run inventory transport route is established:

$$Tc(n) = I + C \tag{1-1}$$

$$minimize\ I = h\left(u_{ri} - q\right) \tag{1-2}$$

$$minimize\ C = \sum_{i=1}^{K} \sum_{i=0}^{L} \sum_{j=0, i \neq j}^{L} \left(C_{kij} + E_{kij}\right) Y_{kij} \tag{1-3}$$

subject to

$$\sum_{i=1}^{n_k} u_{ri} y_{ki} \leq Q_k \tag{1-4}$$

$$\sum_{i=1}^{n_k} v_{ri} y_{ki} \leq V_k \tag{1-5}$$

$$\sum_{i=1}^{n_k} d_{(i-1)i} + d_{0n_k} \cdot y_{ki} \leq D_k \tag{1-6}$$

$$0 \leq n_k \leq L \tag{1-7}$$

$$\sum_{k=1}^{k} n_k = L \tag{1-8}$$

$$\sum_{i=1}^{n_k} y_{ki} = \begin{cases} i = 1, 2, \ldots, L \\ 0, \ldots, others \end{cases} \tag{1-9}$$

$$S_{ki} = S_{k(i-1)} + t_{k(i-1)} + t_{k(i-1)t}, \quad \left(i = 1, 2, \ldots, n_k\right) \tag{1-10}$$

$$t_i = max\{a_i - s_i, 0\}, \quad (i = 1, 2, \ldots, L) \tag{1-11}$$

$$S_i \leq b_i, \quad (i = 1, 2, \ldots, L) \tag{1-12}$$

$$\frac{u_{ri} - q}{q} \leq \varepsilon \tag{1-13}$$

Suppliers	Location	Place of dispatch	Mode of goods consolidation	Distance
S003	Weifang City	Hanting District	Milk run	17
S009	Qingdao City	Economic development District	Milk run	138
S013	Weifang City	Fangzi District	Milk run	13
S019	Qingdao City	Economic development District	Milk run	153
S027	Weifang City	Hanting District	Milk run	15
S032	Weifang City	Fangzi District	Milk run	13
S034	Qingdao City	Licang District	Milk run	133
S035	Weifang City	Gaoxing district	Milk run	12
S074	Weifang City	Xiashan District	Milk run	29
S085	Weifang City	Hanting District	Milk run	13
S089	Weifang City	Gaoxing district	Milk run	5
S123	Weifang City	Economic development District	Milk run	22
S151	Qingdao City	Chengyang District	Milk run	115
S214	Qingdao City	Chengyang District	Milk run	128
S219	Qingdao City	Economic development District	Milk run	154
S233	Weifang City	Kuiwen District	Milk run	14
S257	Weifang City	Gaoxing district	Milk run	11
S272	Weifang City	Hanting District	Milk run	17
S284	Qingdao City	Chengyang District	Milk run	121

Figure 5. The information of 19 suppliers operating milk-run mode.

(1-1) is the total inventory transportation cost and the demand of the user is q. D company sends the order demand q to the specified supplier and requires the quantity u_{ri} of the supplier to be greater than or equal to q; otherwise, the order is invalid. When the supply quantity u_{ri} of the supplier is equal to q, the inventory cost is the lowest. However, from the economic perspective of the supplier, the actual supply quantity u_{ri} will be greater than q because of the load rate of trucks and other reasons.

(1-2) is inventory cost.

(1-3) is the total transportation cost, which consists of fixed logistics cost and variable logistics cost.

(1-4) indicates that, the actual total weight of materials loaded by the vehicle must be less than or equal to the maximum loaded weight of the vehicle.

(1-5) means that on each milk run inventory transportation line, the total volume of materials actually loaded by the vehicle must be less than or equal to the maximum loading capacity of the vehicle.

(1-6) indicates that the total mileage of each milk run inventory transportation route must be less than or equal to the single maximum mileage of vehicles.

(1-7) means that the number of suppliers involved in each cyclic pickup inventory transportation line must be less than or equal to the total number of suppliers.

(1-8) and (1-9) respectively indicate that the transportation department can complete the pickup work at each supplier and ensure that only one vehicle can be sent to each supplier to complete the milk-run work, excluding multiple vehicles arriving at the same supplier for milk-run work at the same time.

(1-10) demonstrates the working time of the vehicle arriving at the next supplier on each cyclic pickup inventory transportation route is equal to the time of the vehicle arriving at the current supplier plus the time required for the vehicle to carry out the cyclic pickup inventory transportation task at the current supplier.

(1-11) and (1-12) respectively indicate that the maximum operating time required to complete the cyclic pickup inventory transportation operation in a single cycle and the time required to carry out the cyclic pickup inventory transportation operation at each supplier must be less than or equal to the corresponding requirements.

(1-13) indicates that the ratio of the difference between the actual delivery quantity and the order quantity to the order quantity should not be greater than the tolerance value, so as to minimize the inventory generated after transportation.

According to this study and the actual situation of D company, the research problem is an NP-hard problem, so it needs to be solved by using an efficient algorithm. We considered the choice to use a simulated annealing algorithm to obtain the optimal solution at a given starting point, as well as end point and a set of customer demand points, to optimally plan the delivery route so that the total travel distance is minimized or the cost is minimized.

In this study, the transportation distance of all suppliers that have chosen cyclic pickup is less than 200 km, and we chose MATLAB as a platform to input values for calculation; the variables “x” and “y” denote the Cartesian coordinates that define the position of a location on the map. The “x” coordinate represents the horizontal position (along the x axis), while the “y” coordinate represents the vertical position (along the y axis). These coordinates allow for the precise location of points on the map, enabling accurate navigation and spatial understanding. Figure 6 shows MATLAB calculated results.

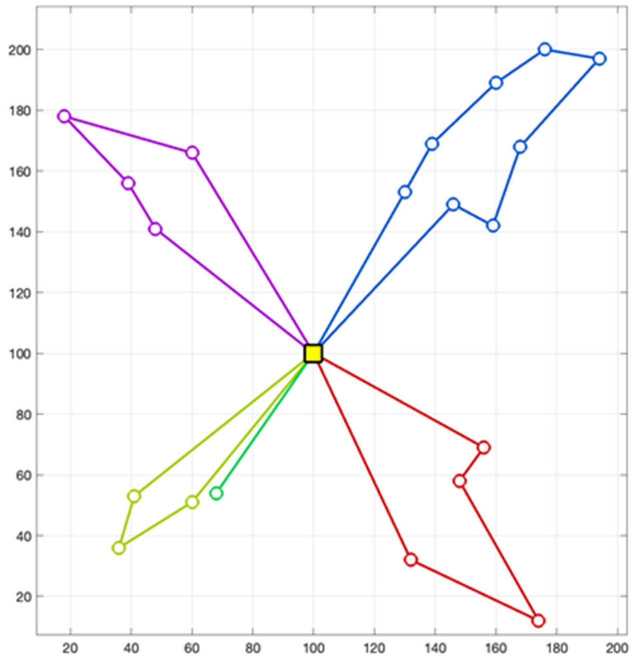

Figure 6. MATLAB simulation results.

x: [37 34 33 10 49 27 65 24 146 199 132 130 147 153 143 169 199 179 164 193 100]
y: [16 14 26 22 172 132 136 141 65 8 61 40 130 161 179 189 147 182 158 158 100]

It can be known from the calculated results that the optimal cost is 1081.6831 after 1383 iterations; the outcome is depicted in Figure 7. Throughout the iterative process, the outcomes exhibited a tendency toward stability, indicating the discovery of a local optimal solution. To prevent prolonged convergence around the optimal solution, the iterative optimization was terminated, resulting in a zero in the final state. The milk-run inventory transportation model, along with the MATLAB simulated annealing algorithm, has helped D company define the optimal transportation route for cyclic pickup inventory. This includes the sequence of cyclic pickup for 19 suppliers within 200 km of D company's VMI warehouse.

The milk-run model provides two significant benefits over the traditional direct supply mode from suppliers: the adjustment of purchase orders and the optimization of transportation routes. The success of these two aspects is crucial in ensuring a smooth inventory transportation process and maximizing benefits for all relevant parties in the supply chain by truly sharing resources.

The findings of the study indicate that the proposed model has taken into account the real-world data and constraints, such as vehicle capacity limits, inventory and the time window of distribution points. By considering these factors, the milk-run inventory optimization model developed in this study was able to define an optimal pickup route, the suppliers on each line and the order of each supplier's pickup. In addition, the model was able to quantify the quantity of pickups, enabling D company to move away from the "near-to-far" and "full-to-stop" status in the milk run operation. This approach helped D company to achieve the goal of joint optimization of inventory transportation under the milk run mode, which provided valuable decision support for the company's operation management.

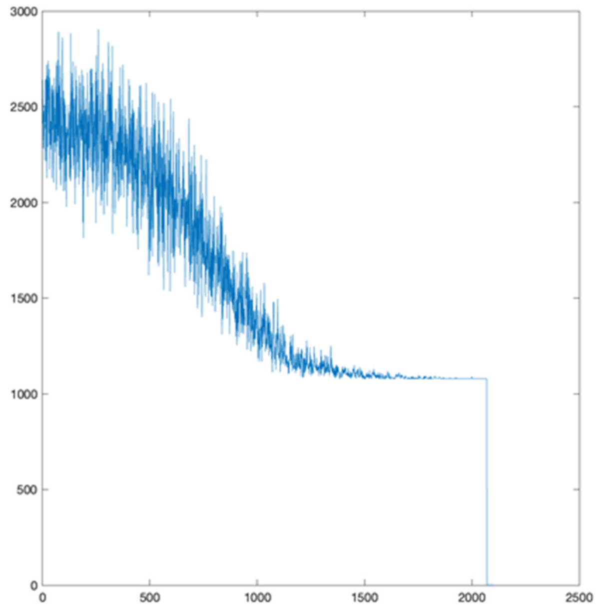

Figure 7. Cost versus iteration.

4.2. Inbound logistics mode of decentralized and centralized distribution

For remote suppliers who cannot participate in the milk-run model i.e., the 198 suppliers following a "manufacturing enterprise-collection centers-D company" model, D company has adopted the inbound logistics mode of decentralized and centralized distribution. Based on the distribution of suppliers and the quantity of goods, D company has selected four regional cargo collection centers in Langfang city, Kunshan city, Yiwu city and Dongguan city for decentralized and centralized operations. In actual operation, decentralized distribution is faced with some difficulties due to problems such as the definition of the quantity of aggregates, the selection of the models, the operation of decentralized distribution and the upward pressure of inventory. This chapter studies the existing problems in the transportation of the decentralized distribution inventory of D company. The four collection centers are located in the following areas:

In Dongguan city, Guangdong province, 115 suppliers aggregate goods in the Dongguan warehousing center, which is 1887 km away from the VMI warehouse of D company.

In Kunshan city, Jiangsu province, 58 suppliers aggregate goods in the Kunshan collecting center, which is 743 km away from the VMI warehouse of D company.

In Langfang city, Hebei province, nine suppliers aggregate goods in the Langfang warehousing center, which is 485 km away from the VMI warehouse of D company.

In Yiwu city, Zhejiang province, 16 suppliers aggregate goods in the voluntary collection center, which is 988 km away from the VMI warehouse of D company.

The following is a data presentation of some suppliers in each cargo handling center, where Distance A is the transportation distance (unit:km) between the supplier and the cargo gathering center. Distance B refers to the transportation distance (unit:km) between the cargo handling center and the VMI warehouse of D company. The data in Figure 8 come from the real data of D company.

In order to establish the model of decentralized inventory transportation, as based on the known conditions of the project of the company D discussed in this paper, the relevant influencing factors have been defined according to the following parameter settings: In order to find the best mode of cargo handling for decentralized inventory transportation, it is necessary to study which factors will have an impact on it. In this study, the VMI warehouse of D company is the only storage center and the parameter settings are shown in Table 2.

Table 2. Symbols of mathematical model.

Set			
$Tc(n)$	Total cost	I	Inventory cost
n	Set of suppliers	C	Transportation cost
m	Set of trucks	k	Set of truck types
Parameters			
H	Unit cost of goods storage		
A_j	Order of suppliers		
A	Max quantity orders of truck		
C_i	Unit cost of transportation		
D_j	Distance		
T_i	Loading weight of truck *i*		
T_j	Weight of order		
L_i	Fuel consumption per hundred kilometers of truck *i*		
p	Price of fuel		
V_i	Average speed of truck *i*		
T_o	Average standing time		
D	Max distance		
$P(D_j)$	The residence time is based on the average residence time of trucks with efficient operation. The longer the freight distance, the higher the probability of trucks choosing to stay, which approximately represents the probability of staying		
r_1^k	The unit time cost for a truck; it mainly considers the labor expenditure of the truck driver		
u_{ij}^k	0–1 variable; it determines whether truck *k* can afford weight of order		
X_{ij}	0–1 variable; it determines whether truck *i* can afford quantity of order		
ε	Tolerance value		

Suppliers	Location	Place of dispatch	Mode of goods consolidation	DistanceA	DistanceB
S004	Dongguan City	Huangjiang Town, Dongguan City	Goods consolidation in Dongguan City	27	1887
S006	Dongguan City	Dongguan City	Goods consolidation in Dongguan City	54	1887
S007	Shenzhen City	Guangming District	Goods consolidation in Dongguan City	56	1887
S011	Dongguan City	Changping Town	Goods consolidation in Dongguan City	7	1887
S014	Huizhou City	Gaoxing District, Huizhou City	Goods consolidation in Dongguan City	72	1887

Figure 8. The information of parts suppliers in four cities.

The decision model for online freight transaction matching order assignment, which optimizes the overall cost of transportation and time for the regional road freight network, is given as follows:

$$Tc(n) = I + Z \tag{2-1}$$

$$I = h\left(A - A_j\right) \tag{2-2}$$

$$minimize\ Z = \sum_{i=1}^{m} \sum_{j=1}^{n} CTC_{ij} X_{ij} \tag{2-3}$$

subject to

$$CTC_{ij} = \sum_{k=1}^{q} \sum_{i=1}^{m} \sum_{j=1}^{n} \left\{ \left(c_i d_j Tj + \frac{d_j}{100} l_i p \right) + \gamma_1^k \left[\frac{d_j}{v_i} + t_0 P\left(d_j\right) \right] \right\} u_{ij}^k \tag{2-4}$$

$$u_{ij}^k T_i \geq T_j,\ i = 1, 2, \ldots, m,\ j = 1, 2, \ldots, n,\ k = 1, 2, \ldots, q \tag{2-5}$$

$$u_{ij}^k d_j \geq D_2,\ k = q \tag{2-6}$$

$$u_{ij}^k d_j \leq D_1,\ k = 1 \tag{2-7}$$

$$\sum_{i=1}^{m} x_{ij} = a_j,\ j = 1, 2, \ldots, n \tag{2-8}$$

$$1 \leq \sum\nolimits_{j=1}^{n} x_{ij} \leq A,\ i = 1, 2, \ldots, m \tag{2-9}$$

$$u_{ij}^k \in \{0, 1\} \tag{2-10}$$

$$0 \leq x_{ij} \leq a_j,\ x_{ij} \in Z,\ i = 1, 2, \ldots, m,\ j = 1, 2, \ldots, n \tag{2-11}$$

$$\frac{u_{ri} - q}{q} \leq \varepsilon \tag{2-12}$$

(2-1) represents the total inventory transportation cost; the user demand is denoted by A_i. When Company D places an order with a supplier, it requires that the quantity of materials supplied by the supplier, denoted by A, must be greater than or equal to A_i; otherwise, the order cannot be established. The inventory cost is minimized when the supplier supplies exactly A_i units of materials.

(2-2) is the inventory cost; the actual supply quantity A is often greater than A_i due to factors such as full truck loads and other economic considerations.

(2-3) indicates that the allocation of freight orders should minimize the overall transportation and time cost incurred by all truck drivers in the region who are responsible for delivering the supplier's materials.

(2-4) represents the total cost of transportation and time incurred by truck driver i of vehicle type k when fulfilling a single freight order from supplier j.

(2-5) requires that the carrying capacity of the truck driven by driver i of vehicle type k must be greater than or equal to the total weight of materials in a single freight order from supplier j.

(2-6) ensures that the sum of the driving distances between driver i of a small light truck and supplier j for pickup work, as well as the sum of the distances between supplier j and the target customer for delivery work change: not exceed the economic critical distance of the small light truck.

(2-7) requires that the sum of the driving distances between driver i of a large heavy truck and supplier j for pickup work, as well as that between supplier j and the target customer for delivery work, are greater than or equal to the economic critical distance of the large heavy truck.

(2-8) ensures that the total volume of freight vehicles is greater than or equal to the order volume.

(2-9) specifies that all orders from supplier j must be assigned to truck driver i.

(2-10) specifies that truck driver i will fulfill at least one order and, at most, A orders.

(2-11) defines the range of values for the decision variable X_{ij}.

(2-12) indicates that the ratio of the difference between the actual delivery quantity and the order quantity to the order quantity should not be greater than the tolerance value, so as to minimize the inventory generated after transportation.

This model represents an integer programming-type transportation problem, which is a difficult problem to solve because it is NP-hard. To solve this problem, we have adopted the linear programming relaxation method. This involves relaxing integer variables to real variables and introducing relaxation and dummy variables to convert the problem into a linear programming problem, which can be solved by using a linear programming algorithm. The integer solution is then obtained by substituting variables back into the original problem. This involves introducing relaxation variables for each constraint and turning them into equality constraints, as well as introducing dummy variables to restrict each variable to integer values. Finally, we use the substitution method to obtain the integer solution by repeatedly plugging the variables into the original integer programming problem until an integer solution is obtained.

In order to verify the correctness of the model in this study, we selected part of the actual dispersed and distributed inventory transportation data of D company for calculation. According to the actual situation, we know that the transportation distances between the four warehousing centers and the VMI warehouse of D company are 1887 km, 743 km, 485 km and 988 km, respectively.

The two main transport vehicles are as follows:

4.2-m truck: The expected transport distance is less than 750 km, the average salary of the truck driver is 25 per hour, the average residence time of a truck is 10 hours and the residence probability conforms to the geometric distribution, the value is 0.4 in this example.

13-m truck: The expected transport distance is less than 2000 km, the average salary of the truck driver is 35 per hour, the average residence time of a truck is 20 hours and the residence probability is consistent with the geometric distribution. The value is 0.9 in this example.

The diesel oil market price at the time was 7 per L, and the storage unit cost was 200. We randomly selected one supplier from each of the four cargo handling centers, making a total of four suppliers. The data in Figure 9 come from the real data of D company. Figure 10 is the information of selected trucks.

Suppliers	Location	Place of dispatch	Mode of goods consolidation	DistanceA	DistanceB	Quantity of order
S004	Dongguan City	Huangjiang Town, Dongguan City	Goods consolidation in Dongguan City	27	1887	328
S208	Kunshan City	Kunshan City	Goods consolidation in Kunshan City	4	743	36
S039	Tianjin City	Development District, Tianjin City	Goods consolidation in Langfang City	98	485	94
S015	Zhejiang Province	Hengdian Town	Goods consolidation in Yiwu City	43	988	137

Figure 9. Information of selected suppliers.

Suppliers	Type of truck	Loading capacity	Transportation cost	Fuel consumption	Average speed	Quantity of order
S004	13m	35	0.005	40	45/h	328
S208	4.2m	10	0.008	15	30/h	36
S039	4.2m	10	0.008	15	30/h	94
S015	13m	35	0.005	40	45/h	137

Figure 10. Information of selected trucks.

According to the above research, D company sends the order quantity A_i to the specified supplier and requires the delivery quantity A of the supplier to be greater than or equal to A_i; otherwise, the order is invalid; the calculated values are shown in Figure 11.

Suppliers	Quantity of order	Number of trucks	Quantity of transportation	Inventory	Inventory cost
S004	328	10	350	22	4400
S208	36	4	40	4	800
S039	94	10	100	6	1200
S015	137	4	140	3	600

Figure 11. Inventory cost after a single transport cycle.

The single-cycle transportation cost is as follows:

$$CTC_{ij} = \sum_{k=1}^{q} \sum_{i=1}^{m} \sum_{j=1}^{n} \left\{ \left(c_i d_j Tj + \frac{d_j}{100} l_i p \right) + \gamma_1^k \left[\frac{d_j}{v_i} + t_0 P\left(d_j \right) \right] \right\} u_{ij}^k.$$

Suppliers	Distance of transportation	$(c_i d_j Tj)$	$\frac{d_j}{100} l_i p$	$\gamma_1^k \frac{d_j}{v_i}$	$\gamma_1^k[t_0 P(d_j)]$
S004	1914	3349.5	5359.2	1488.67	787.5
S208	747	239.04	784.35	622.5	100
S039	583	466.4	612.15	485.83	100
S015	1031	721.7	2886.8	801.89	787.5

Figure 12. Transportation cost of a single transport cycle.

Figure 12 shows calculated results of transportation cost after a single cycle. Since the data we selected are all actual cases and transportation orders that have been formed, the assumption probability u_{ij}^k is 1, and the final cost is as follows in Figure 13.

Suppliers	Inventory cost	Cost of transportation	Total cost
S004	4400	10984.87	15384.87
S208	800	1745.89	2545.89
S039	1200	1664.38	2864.38
S015	600	5197.89	5797.89
Total	7000	19593.03	26593.03

Figure 13. Total costs.

The data in Figure 14 come from the real data of D company.

Cost Statement

	S004	S208	S039	S015	TOTAL
Order quantity	328	36	94	137	595
Warehouse cost	4,800	1,000	1,400	800	8,000
Transportation cost	11,644	1,816	1,731	5,458	20,649
human cost	-	-	-	-	-
Other costs	-	-	-	-	-
Total cost	16,444	2,816	3,131	6,258	28,649

Figure 14. Historical operating costs for D company.

By analyzing the historical order data of D company as presented in Figure 14, it is evident that the information provided by the company selectively omits factors such as management personnel and other costs, likely due to commercial considerations. However, for the purposes of this study, the focus remains solely on investigating inventory and transportation costs, thereby aligning with the objectives of this study.

The outcomes of this research demonstrate the efficacy of the proposed model and reconciliation method in addressing the transportation challenges associated with the dispersed and aggregated inventory. The application of these approaches leads to significant cost reductions of 6.44, 9.59, 8.52 and 7.36% across four separate orders, with an average reduction of 7.18% across all orders. This implementation enables the minimization of distribution costs while satisfying the requisite constraint conditions.

The results of this study demonstrate that the proposed model and solution method can effectively solve the transportation problem of dispersed and assembled inventory while minimizing the distribution cost under the premise of satisfying the constraint conditions. Regarding D company's operating status, the inventory transportation optimization model established in this study can identify the optimal cost of each line in the decentralized aggregation mode, at the best model selection and other factors. As a result, it is possible to obtain the logistics organization mode with the lowest total cost of inventory transportation, thereby achieving the goal of joint optimization of the inventory transportation under the decentralized aggregation mode. This model provides a decision reference and decision-making support for D company's operation management.

5. Discussion

In this study, we have focused on the joint optimization of inventory transportation under two inbound logistics modes: the milk run and decentralized aggregation, with a specific emphasis on projects operated by D company. The findings have shed light on the potential benefits of adopting the milk-run mode in the front-end of the decentralized cargo handling area to reduce overall logistics costs. However, due to limitations in transportation resources and increased complexity, D company currently does not implement the milk-run mode in this specific area. Our investigation entailed an independent approach to optimize inventory transportation under both the milk-run mode and decentralized aggregation mode. By establishing separate mathematical models for each mode, we sought to determine the lowest total cost of inventory transportation. The convergence of the milk run and dispersed and assembled parts in the VMI warehouse also prompted the consideration of a mixed mode, opening up avenues for future research on the complexities of supply chain logistics systems.

As compared to previous studies, we share a common objective of identifying cost-effective solutions for logistics optimization. However, our approach differs in terms of the specific methodologies, the optimization models and the scope of the study. While previously published papers focused on a broader industry context, our research is empirical, as our investigation was tailored to the specific operations of D company, which has provided valuable insights for similar companies' supply chain management. This study is novel in that it addressed the challenges faced by D company in adopting the milk-run mode in the front-end of the decentralized cargo handling area. Our findings demonstrate how such implementation could lead to significant cost reduction in logistics operations. The specific focus on D company's projects also contributes to a better understanding of supply chain dynamics in a real-world setting.

The benefits of our approach lie in its potential to optimize logistics operations and enhance supply chain efficiency for D company. By offering tailored solutions for their unique context, our research helps to overcome specific challenges faced by D company in managing inventory transportation. While our investigation is specific to D company's projects, the insights gained have implications beyond their scope. The optimized inventory transportation approaches can be adapted and applied to other industries facing similar logistics challenges. The application of our findings can lead to improvements in supply chain management practices for a broader range of companies.

6. Conclusions

This paper delves into a comprehensive analysis of the VMI-TPL operation mode employed by D company, while considering relevant literature and theories. The driving forces behind the integration of VMI and TPL have been systematically examined. D company's current operation project, which employs two cargo flow modes, i.e., the milk run and decentralized aggregation, has been thoroughly investigated, taking into account information system management, logistics resource integration and logistics service capabilities. In pursuit of optimizing the inventory transportation under the VMI-TPL mode, we have proposed a joint optimization model based on the milk run. The process and strategic decision model for the milk run under the VMI-TPL mode have been developed, addressing core challenges encountered in the milk-run process. Additionally, a model has been established to address issues related to the path, quantity, supplier changes and path changes under cyclic delivery operations. This model provides D company with a quantitative framework for rapid decision-making when facing such challenges, enabling efficient and effective optimization of the inventory transportation and overall supply chain performance. Furthermore, the paper investigates the joint optimization of inventory transportation based on decentralized aggregation under the VMI-TPL mode. From the perspective of the TPL company D, an overall optimization model for the total cost of the supply chain under the centralized goods. This model considers the supply chain logistics network comprising multiple suppliers, a single TPL plan and a single manufacturer, and it utilizes G company's production plan and future demand forecast transmitted by D company's information management system as the decision-making basis. The study not only offers D company scientific and quantitative guidance on determining the inventory quantity and vehicle types for the decentralized aggregation mode for practical operation management, but it also provides valuable support for decision-making under dynamic conditions, such as changes in order quantity and supplier adjustments. By doing so, it facilitates further joint optimization of inventory transportation based on the decentralized aggregation mode.

In conclusion, this study contributes significant insights change into the optimization of inventory transportation under the VMI-TPL mode for D company. The proposed models and decision-making support provide a robust foundation for enhancing supply chain efficiency and performance. Furthermore, the research opens avenues for future investigations, offering potential opportunities for more refined joint optimization strategies under various logistics scenarios.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare there is no conflict of interest.

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