Optimization of Multi-Supplier Collaborative Transportation Based on K-Shortest Path Algorithm

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Title page

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ORIGINAL ARTICLE(or REVIEW)

Optimization of Multi-Supplier Collaborative Transportation Based on K-Shortest Path Algorithm

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Abstract: With the wide application of big data and artificial intelligence technology in road traffic, road planning makes logistics and transportation services more efficient. For the supplier's transportation service problem, a multi-supplier collaborative transportation strategy is designed in this paper. First, we establish a model to minimize the transportation cost, then we simulate a path diagram and calculate the optimal transportation paths of suppliers based on Dijkstra's algorithm. In addition, we obtain multiple alternative paths with K-shortest path algorithm. Finally, simulations of collaborative transportation for suppliers are performed in three scenarios and the results are used to prove the effectiveness of the proposed collaborative transportation strategy. This strategy not only can strengthen the synergistic cooperation among suppliers, but also cultivate the potential customer. Furthermore, it also could improve the flexibility of the supply chain, maximize the overall efficiency and provide a new solution for the development of logistics and transportation services.
Keywords: Artificial Intelligence • Collaborative transportation • Path optimization • K-shortest path algorithm • Value chain

1 Introduction

With the widespread of IoT, big data, and artificial intelligence technologies in transportation networks, smart transportation make it easier for people to get around. The intelligent transportation system (ITS) was formed by combining new technological elements such as big data and artificial intelligence [1]. Through the effective integration of sensor technologies, data communication transmission technologies, electronic control technologies, advanced information technologies and computer processing technologies, a dynamic, accurate, real-time and efficient intelligent management system has been established [2]. Advanced technologies in ITS make the road traffic more intelligent, increase the road traffic utilization effectively, decrease the energy consumption, improve the quality of the air environment, and ensure the driving traffic safety. Therefore, ITS is considered as an effective way to solve urban congestion and improve driving safety [3-4]. Dynamic Route Guidance System (DRGS) is one of the core technologies to achieve intelligent transportation systems [5]. Through the information from Global Positioning System (GPS) and Vehicle Navigation System (VNS), the DRGS can obtain a large amount of real-time and accurate traffic network data. Then, intelligent optimization algorithms are used to plan the optimal route for users to meet the real-time traffic environment. In addition, the Vehicle Navigation Systems (VNS) has been widely used in driving vehicles. In some developed countries, It is mainly used in public transportation, emergency vehicle management, electronic toll stations and traffic information collections [6]. In the era of big data, it is crucial for the

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intelligent transportation system with fast traffic information updating, dynamical route guidance, effective information extraction and feedback [7].

Path optimization algorithms are one of the key technologies for the implement of DRGS. These algorithms can be classified into two aspects: local path optimization algorithms and global path optimization algorithms. The former calculates a safe path through optimization algorithms without complete information about the environment but from the surrounding environment information. A general local path optimization algorithm includes an artificial market method, speed barrier method, vector field histogram and so on. Local path optimization methods generally have few parameters and easy implementation, so these algorithms have strong robustness and can be combined with other algorithms to form a new optimization algorithm. However, the disadvantages are great calculation work, close dependence on the environmental information and poor real-time performance. Compared with the global path optimization algorithm, it is generally used in smaller scopes.

The global path optimization algorithm optimizes the path based on the existing map information to find an optimal path from the starting point to the target point. Global path optimization algorithms include ant colony algorithm [8], genetic algorithm [9], deep learning algorithm [10] and Dijkstra algorithm [11]. The ant colony algorithm was proposed by Dorigo, concerning the property that an ant colony leaves pheromone marks during foraging. It is possible to determine the shortest path between two points by determining the concentration of pheromone. Additionally, it is a distributed computing method that combines positive and negative feedbacks with each other, so it is robust and easily to find an optimal path without affecting each other ants. However, it also has some disadvantages, such as slow convergence speed and easily falling into local optimal solutions. To deal with these problems, Liu et al. [12] reallocated the pheromones of the traditional ant colony algorithm based on the Dijkstra's algorithm, where each ant in the model used a combination of hierarchical advance and raster plane method to search for paths. The Bessel curve was used to improve the smoothness of the paths, which increased the convergence speed and was applied in the path planning of underwater robots. Zhang et al. [13] applied an improved ant colony algorithm in a multi-scenic spot path planning, and demonstrated the traversal of nodes by eliminating the restriction of the taboo table in the ant colony algorithm to improve the overall efficiency. The genetic algorithm was proposed by Bremermann in the United States in 1960 [14]. It generates optimal solution by simulating organisms towards a more adaptive direction. It simulates evolution by selection, crossover and mutation of genetic operators to produce new populations suitable for the environment. Tong et al. [15] improved the operators of the genetic algorithm for the welding path, which improved the iteration efficiency and enabled the algorithm to obtain the optimal welding path. Compared with other global path optimization algorithms, the deep learning algorithm can prompt mobile robots to learn and plan feasible movement paths autonomously by learning the intrinsic laws of path planning samples. It is suitable for the scenario of dynamic obstacle avoidance of robots with a large number of training samples. It may be one of the key directions for path planning in the future. For vehicles with safety constraints, Yu et al. [16] proposed a path planning algorithm based on deep learning algorithm from starting point to ending point and applied in the lunar rover. Compared with classical path planning algorithm, it has a higher security.

Dijkstra's algorithm was first proposed by Dutch computer scientist Dijkstra in 1959 with implemented based on the greedy idea [17]. Within this method, firstly, it saves the distance between the starting node and other connected nodes, then selects the point with the shortest path as the next marker node, and finally finds the shortest routes. It is a simple method and can easily solve the single source shortest path problem. Zhang et al. [18] first used Dijkstra's algorithm to find feasible evacuation routes, then combined with the breadth search algorithm to find the global optimal paths based on real-time dynamic information updating. The simulation results showed that it could effectively deal with the personnel emergency evacuation. Wu et al. [19] planed paths with vehicle road risk resistance and road condition factors to achieve an optimal selection of paths with reduced transport cost and time-saving by using network topology, analysis methods of geocoding, and the Dijkstra algorithm for effective integration. Xie et al. [20] considered three cases of traffic paths and calculated the shortest distance paths of the line network based on an improved Dijkstra's algorithm. Zhang et al. [21] studied the problem of path selection based on reliability theory in the same path length, and transformed the K-shortest path problem into a reliability optimization problem. In the K-shortest path, the edges that are not contained in the set of K-shortest paths are insignificant, and only the sub-networks with the K-shortest paths are considered. The factorization algorithm was used to calculate the reliability of each path, and the one with the highest reliability was returned to the set of paths.

In recent years, numerous researchers have studied on path optimization. The combination of path optimization and logistics is a prominent feature in the intelligent transportation. Yu et al. [22] considered the problem of minimizing vehicle supplier distribution by dividing the set of retailers into a subset as small as possible by designing a subset division strategy. Chen et al. [23] found that paths were not always selected based on cost principle of the shortest path in logistics services, and proposed an inverse optimization method for solving the path planning model by using a machine learning update algorithm. Xu et al. [24] transformed the reverse logistics collaborative distribution path planning problem into a series of static optimization problems, and proposed a two-stage solution strategy for dynamic path optimization. A coordinated real-time dynamic path planning model for multiple distribution centers with minimum total transportation cost and maximum customer satisfaction was established. Kong et al. [25] studied the distribution shortest path problem from distribution centers to multiple customers, and solved the variable-speed vehicle path problem with time windows and capacity constraints for the existence of multiple access roads between two points considering the passage time and road condition factors. This has important influence on the vehicle delivery path optimization problem with complex road conditions.

Based on the above researches, this paper studied the procurement and transportation problem of supply chain and designed a multi-supplier combined transportation strategy. Firstly, we proposed a mathematical model to minimize the transportation cost. Then we simulated a complex path diagram and obtained multiple alternative paths by K-shortest path algorithm. In addition, three scenarios were considered in the simulation calculations. Finally, the results validated the effectiveness of the collaborative transportation strategy. The designed collaborative transportation strategy for suppliers not only strengthens the cooperation of enterprises, but also improves flexibility of supply chain and achieves the maximization of overall value in this paper. The organization of this paper is given as follows. Section 2 describes the characteristics of the transportation service and the mathematical model. Section 3 introduces the implementation of the method for computing multiple alternative paths. Numerical simulations are performed and the effectiveness of the supplier's combined transportation strategy is verified in Section 4. Finally, the study is summarized in Section 5.

2 Problem Description and Modeling

The supplier provides transportation services to the manufacturer and has a limited capacity of vehicles. There are multiple paths with different road conditions between the manufacturer and the supplier. Multiple vehicles depart from supplier's distribution center, serve the manufacturer within a defined time limit, and return to the distribution center after completing the service. The common objective functions for route optimization are mainly maximizing total transportation volume, optimal transportation routing, minimizing vehicle waiting time, or minimizing transportation cost. In particular, minimizing transportation cost is a general optimization objective in supplier distribution transportation. We simplify the complicated geographical route by planarization and virtualization processing, and use the graph theory G(V, E) to describe the relationship between the sets of nodes. V= {1,2,...,v} in graph G is the set of nodes, where V is the total number of nodes and E is the set of edges in graph G as given in

$$E = \{(i, j); i, j \in V, i \neq j\}$$

Then, we have the following mathematical model in (1) to illustrate the composition of transportation costs. The definition of the variables are given in Table 1.

Table 1 Definition of variables

Variables	Definition
Q	Vehicle capacity limit
d_{ij}	Distance from node i to node j
t_{ij}	Time cost from node i to node j
e_{rc}	The earliest time for supplier r to arrive at the customer c
l_{rc}	The latest time for the supplier r to arrive at the customer c
q_{rm}	Quantity of raw materials of the category m from supplier r
g_r	Total number of raw materials in the distribution center of supplier r
s_{rk}	Vehicle k departure time from distribution center at supplier r
w_r	Service hours of the distribution center at supplier r
s_{ki}	Time for vehicle k to reach node i
s_{kj}	Time for vehicle k to reach node j
s_c	Time for the customer c requested to delivery
p_r	Penalty fees for supplier r
a	Unit penalty cost for early vehicle arrival
b	Unit penalty cost for late arrival of vehicles
c_1	Transportation cost per unit distance
c_2	Average unladen transportation cost
v	Average speed of vehicle transportation per unit time
x_{ijk}	The decision variable of whether vehicle k

reaches node j from node i

$$\text{Min}(\sum_{k\in K}\sum_{i\in V}\sum_{j\in V} c_1 \times x_{ijk} \times d_{ij} + \sum_{k\in K}\sum_{i\in V}\sum_{j\in V} c_2 \times x_{ijk} + \sum_{r\in S} p_r) \quad (1)$$

subject to :

$$\sum_{m\in n} d_{rm} - g_r \le 0 \quad (2)$$

$$\sum_{m\in n} q_{rm} \le \sum_{k\in K} Q_k \quad (3)$$

$$s_{kj} = s_{ki} + t_{ij} \quad (4)$$

$$\sum_{i\in V-\{j\}}\sum_{k\in K} x_{ijk} = \sum_{i\in V-\{j\}}\sum_{k\in K} x_{jik} \quad (5)$$

$$\sum_{j\in V-\{r\}}\sum_{k\in K} x_{jrk} = \sum_{j\in V-\{r\}}\sum_{k\in K} x_{rjk} \quad (6)$$

$$P_r = a \times \max((s_c - e_{rc}), 0) + b \times \max((l_{rc} - s_c), 0) \quad (7)$$

$$x_{ijk} = \begin{cases} 1 & \text{vehicle } k \text{ to reach node } j \text{ from node } i \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

$$\{i, j\}\varepsilon E,\ k\varepsilon K$$

Constraint (2) describes that the total capacity shipped from the supplier's distribution center is not greater than the total capacity of the supplier's distribution center. Constraint (3) displayes that the total weight of the required goods is less than the rated weight of the supplier's total vehicles. Constraint (4) is the time for vehicle k to reach node j from node i. Constraint (5) means that the vehicle must leave a node after arriving at that node. Constraint (6) means that the vehicle leaves the distribution center and also will return to the distribution center at same route. Constraint (7) means that the penalty cost paid by the vehicle for the violating time window requested by the customer. Constraint (8) indicates whether vehicle k passes through node j from node i.

3 Multi - path planning implementation method

Dijkstra's algorithm is simple, easily applicable, robust, and high reliable method in path planning. It is used to solve the shortest path problem with weights in graph. The main feature is to expand enough layers from a starting point to a target point, where the weighted values in the graph is not negative. The shortest paths are generated with increasing order of length, when a starting point and a target point are given in an undirected graph. Actually, Dijkstra's algorithm is used to discover the shortest distance from the starting point to each point in the network. The K-shortest path algorithm is an extension of the shortest path problem. It uses the idea of deviated path algorithm in the recursive method and is applicable to non-negative weighted directed acyclic graph structures for the optimization of multiple paths. The network searches for paths from the starting point to the target point with a non-decreasing order, and get a set of shortest paths to meet users' requirements by considering different paths in the greatest extent. This paper first calculates the optimal path based on Dijkstra algorithm, then disconnects the nodes of the optimal path, and searches for all the path sets that can reach the specified node by deviating from the path algorithm. The pseudo-code of Dijkstra algorithm and k-shortest path algorithm are shown in Table 2 and Table 3 respectively.

Table 2 The pseudo-code of Dijkstra's algorithm

```
// Dijkstra's algorithm for single-source shortest paths
// Input: A weighted connected graph G = {V , E} and its
   node s
// Output : The length dv of a shortest path from s to v in V
   initialize (Q)
// Initialize node priority queue to empty for every node v
   in V do
   dv←∞, pv null
Insert (Q, v, dv) // initialize node priority in the priority
queue
Ds←0; Decrease(Q, s, ds) // update priority of s with ds
VT ← ϕ
For i←0 to |v| - 1 do
     u*←Delete Min(Q) // delete the minimum priority
     element
      VT←VTU{u*}
For every node u in V – VT that is adjacent to u* do
     if du* + w (u*, u) < du
     du←du* + w (u*, u); pu←u*
Decrease(Q, u, du).
```

Table 3 K-shortest path based on Dijkstra

1. Initialize a collection of nodes.
2. Select the node closest to the source node and mark it.
3. Calculate the distance from the labeled node to the next node.
4. Update the minimum distance.

5. Record the shortest path.
6. Place the shortest path in the result list and select the last one in the result list.
7. Create disabled links and nodes based on the path.
8. Find the shortest path from the connecting node to the end point, according to the modified adjacency matrix.
9. Concatenate paths, or add alternate paths if they are not duplicated.
10. Alternate paths are sorted with ascending order, and the shortest, one is added to the result list.
11. Continue to step 6 until no new paths are added.
12. Output all paths.

4 Numerical simulation results

4.1 Product transport multiple path problem

As a vital component of the modern service industry, the modern logistics industry has greatly theoretical and practical significance to promote the development of the national economy and improving the competitiveness of the international market. Transport services take an important position in the logistics system with great pressure on the low logistics costs and decreasing energy and reducing emissions. Especially with the increase of fuel prices, the issue of smooth and efficient logistics and transportation services is an important part of the research. Depending on the origin of the order, the supplier selects all the path nodes that may pass through by using big data or personnel's historical experience. Firstly, we processed the complex routes in real life by flattening them and looking at the length between nodes as the route distance. Secondly, vehicles pass through each route in the same way without traffic flow and congestion. Then only how to plan a feasible route is considered without the time requirement of passing through a specific section. Finally, we got a complex path diagram with the path planning problem. The path diagram is shown in Fig. 1. In logistics transportation, it is assumed that the brown marker point represents supplier and the green marker point represents manufacturer. We find the shortest distance from the start point to the end point by Dijkstra's algorithm. The shortest path in red is 1-8-12-16-19-22 and the total distance is 101+98+132+91+86=491. The shortest path in blue is 2-4-5-13-15-19-22 and the total distance is 72+76+71+69+98+86=472. Many researches on the direct transportation strategy of suppliers mainly focus on how to divide multiple customers who suppliers can dispatch fewer vehicles to provide services. There are not many studies on the transport service from the perspective of multiple paths. Therefore, based on the two shortest paths in Figure 1, we further studied the problem of suppliers providing transportation services to manufacturers.

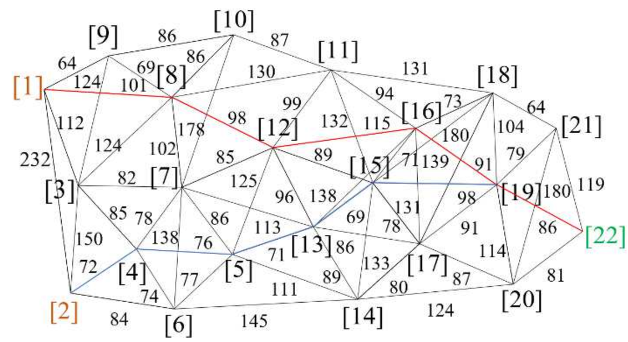

Figure 1 Road network diagram

Fuel consumption is a big part in the transportation cost, due to the effect of speed, gradient, load capacity, weather, and road conditions. Here, weather and road conditions are not controllable. In the simulation, based on the historical experience, we set the unit of one vehicle transportation cost to be 15 RMB/km, the average cost of the empty load to be 10 RMB/km and the average speed of all vehicles to be 45km/h. The vehicle has the same go and return route. We simulated 100 times for each of these two paths by interrupting the optimal path nodes and used the simulated routes as alternative paths. Fifteen paths are selected from the alternative path libraries of these two suppliers and the total cost of a single vehicle distribution transport round trip is calculated, as shown in Table 4 and Table 5. Here, we do not take into account the early and delayed arrival of the vehicle at the manufacturer.

Table 4 Supplier 1 alternative path scheme

Number	Path	Total distance (km)	Total cost
a1	1-8-12-16-19-22	491	12275
a2	1-8-11-16-19-22	502	12550
a3	1-9-8-12-16-19-22	523	13075
a4	1-8-11-18-21-22	545	13625
a5	1-9-12-13-17-19-22	558	13800
a6	1-8-12-16-15-19-22	569	14225
a7	1-9-8-10-11-16-19-22	577	14425
a8	1-8-11-16-15-19-22	580	14500
a9	1-3-4-5-13-15-19-22	597	14925
a10	1-8-11-12-16-19-22	622	15550
a11	1-8-12-13-17-15-19-22	643	16075
a12	1-3-4-5-13-16-19-22	659	16475
a13	1-3-4-6-5-13-15-19-22	672	16800
a14	1-8-11-16-15-19-20-22	689	17225

a15	1-8-7-13-12-16-19-22	704	17600

Table 5 Supplier 2 alternative path scheme

Number	Path	Total distance (km)	Total cost
b1	2-4-5-13-15-19-22	472	11800
b2	2-6-14-17-20-22	477	11925
b3	2-6-5-13-15-19-22	485	12125
b4	2-4-5-14-17-20-22	507	12675
b5	2-6-5-14-17-20-22	520	13000
b6	2-4-5-13-16-19-22	534	13350
b7	2-6-14-15-19-22	546	13650
b8	2-6-4-5-13-15-19-22	558	13950
b9	2-6-14-17-15-19-22	571	14275
b10	2-4-7-12-13-15-19-22	585	14625
b11	2-4-3-7-13-15-19-22	605	15125
b12	2-4-5-12-13-15-19-22	622	15550
b13	2-4-5-13-16-19-20-22	643	16075
b14	2-6-5-13-16-19-20-22	656	16400
b15	2-4-3-9-12-16-19-22	671	16775

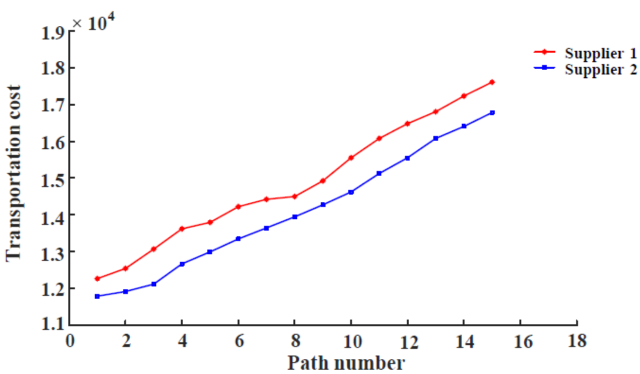

Figure 2 Comparison of total transportation cost of alternative path

We statistically analyzed the transportation cost of these two suppliers. As shown in Figure 2, the costs of all transportation for supplier 2 are lower than supplier 1 in general, which provides an opportunity for suppliers to achieve collaborative transportation. Therefore, we explored the issue of combined distribution and transportation with the other suppliers to avoid the risk of huge compensation when the specific supplier fails.

4.2 Supplier collaborative transportation path problem

Good supply service capability is the basis for the development of modern logistics. Customer's demand is the motivation of logistics and transportation. In the supply chain, manufacturer needs multiple suppliers to provide raw material transportation services for their production. Therefore, it becomes extremely critical for suppliers to choose an efficient transportation method. The proposed collaborative transportation method provides an idea to solve the product transportation problem in this paper. We assume that these two suppliers provide transportation services of raw materials for the manufacturer in the supply chain. The manufacturer assigns different quantities of order requirements to these two suppliers, who have the same load capacity of vehicles, and supplier 1 has 10 transport vehicles and supplier 2 has 15 transport vehicles. A prerequisite for two suppliers to complete the collaborative transportation is that supplier 1 is unable to complete all orders in time, but supplier 2 is able to provide additional orders. In addition, supplier 1 does not dispatch vehicles and provide any assistance for supplier 2. Then, we considered three scenarios for supplier 1 delivering supplier 2's orders, as shown in Table 6. The unit of transportation cost for supplier 2 to transport supplier 1's order is 22 RMB/km, the unit of raw materials cost is 6 RMB and the profit of supplier 2 for the unit of raw materials is 4 RMB.

The horizontal axis represents the 15 alternative paths for supplier 1 and the vertical axis represents the transportation cost. The red curve represents the separate transportation cost for supplier 1 own orders and the others represent the transportation costs for supplier 1 itself when suppliers adopt the collaborative transportation strategy. The collaborative transportation cost consists of two parts. The first part of the cost is the transportation cost incurred by supplier 1 when choosing the specified alternative route and the second part of the cost is the transportation cost incurred by supplier 2 when choosing one of the alternative routes to complete supplier 1's orders. In scenario 1, as shown in Figure 3, when supplier 1 selects the 12th path, the transportation costs of its own orders in red curve are higher than the costs of collaborative transportation represented by the other 10 curves with different colors. The result shows that the costs of collaborative transportation above the point of the red curve are greater than the separate transportation cost for supplier 1 own orders and the collaborative transportation costs below the red curve point are less than the separate transportation cost for supplier 1 itself. This indicated that collaborative transportation could effectively reduce the transportation cost of supplier 1.

Table 6 Supplier order allocation

	Separate transportation allocation		Collaborative transportation allocation	
scenario	supplier 1	supplier 2	supplier 1	supplier 2
1	4800	1200	3400	2600

2	4800	1200	2300	3700
3	4800	1200	1800	4200

Table 7 Supplier vehicle allocation

	Separate transportation allocation		Collaborative transportation allocation	
scenario	supplier 1	supplier 2	supplier 1	supplier 2
1	10	3	7	6
2	10	3	5	8
3	10	3	4	9

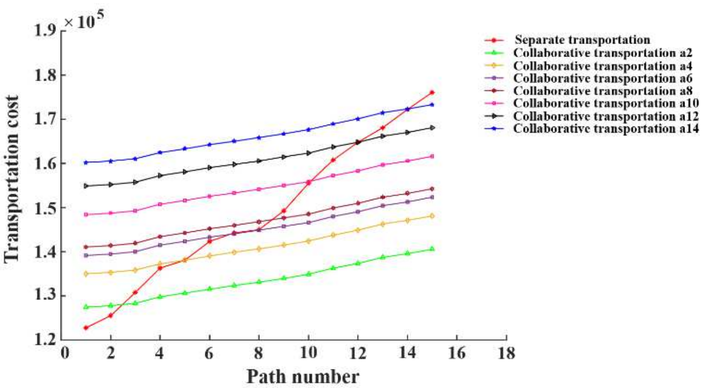

Figure 3 Comparison of supplier 1's separate and collaborative transportation

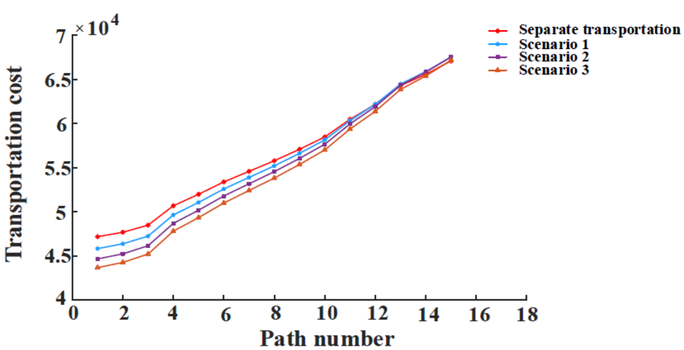

Figure 4 Comparison of supplier 2's separate and collaborative transportation

In these three scenarios, as shown in Table 6, the transportation cost of supplier 2 is shown in Figure 4. The red curve represents the separated transportation costs of supplier 2 to complete its own orders. Curves with other colors represent the transportation costs of supplier 2 after adding orders from supplier 1. This showed the collaborative transportation costs of supplier 2 are lower than the separate transportation costs for supplier 2 own orders. Additional, while the number of orders from supplier 1 increases, the number of transportation vehicles for supplier 2 also increases, but transportation costs for supplier 2 decreased. As shown in Table 7, the collaborative transportation of suppliers reduces the vehicle utilization of supplier 1 but increases the vehicle utilization of supplier 2. The results show that the vehicle resource of Supplier 2 achieves the maximum resource utilization efficiency.

5 Conclusions

In this paper, we analyzed the path planning problem for collaborative transportation of multi-supplier vehicles under the condition of optimal path node disruption. There are multiple transportation paths from the supplier to the manufacturer. Firstly, we obtained the optimal path based on Dijkstra's algorithm. Then all alternative paths were constructed by disconnecting the nodes of the optimal route one by one. Thereafter, a model for minimizing transportation costs was proposed and a multi-supplier collaborative transportation strategy was designed. Finally, the effectiveness of the combined transportation strategy is verified by simulation in three scenarios. The results indicated that the proposed combined transportation strategy of suppliers not only strengthens the synergistic cooperation among suppliers, but also cultivates the potential customer for suppliers in this paper. It not only can guarantee the satisfaction of manufacturer but also make the cooperative relationship between these three parties closer. From the perspective of the value chain, it not only can improve the flexibility of supply chain and achieve maximization of the overall benefit, but also can provide new solutions for the development of logistics and transportation path planning.

7 Declaration

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows:

Ai-Hui Wang, Wu-Dai Liao: Conceptualization of the structure of the article and guidance of the writing method, review;

Xiao-Bo Han: Analysis of writing methods, Writing original draft;

Ping Liu: Article review, Writing revision guidance;

Jing-Wen Song, Da-Ming Li: Review, Editing

All authors read and approved the final manuscript.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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Appendix

Appendix and supplement both mean material added at the end of a book. An appendix gives useful additional information, but even without it the rest of the book is complete: In the appendix are forty detailed charts. A supplement, bound in the book or published separately, is given for comparison, as an enhancement, to provide corrections, to present later information, and the like: A yearly supplement is issue.